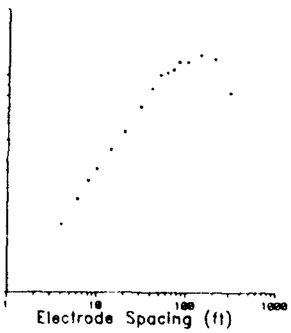
AD-A255 749

TECHNICAL REPORT GL-92-12

(2)

US Army Corps of Engineers



ASSESSMENT AND SELECTION OF AN AUTOMATED ELECTRICAL RESISTIVITY INTERPRETATION PROCEDURE

by

Janet E . Simms, Dwain K. Butler

Geotechnical Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

8468

411412

August 1992
Final Report

92 9 17 024

GEOTECHNICAL LABORATORY

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1992

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Assessment and Selection of an Automated Electrical Resistivity Interpretation Procedure

5. FUNDING NUMBERS
Project AT40,
Task WS,
Work Unit 001

6. AUTHOR(S)
Janet E. Simms
Dwain K. Butler

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAE Waterways Experiment Station
Geotechnical Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report
GL-92-12

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The Defense Science Board and Joint Chiefs of Staff have idendified ground-water supply development capability as a major technological shortfall. The goal of research and development under the Corps of Engineers Water Supply Program is to provide the military with the capability to detect new ground-water sources to support operations, aid in humanitarian relief programs, and as a part of nation assistance. The detection of ground-water sources will be achieved through an integrated, automatic data acquisition and interpretation capability for electrical resistivity and seismic refraction data. This report addresses the requirements for the resistivity data acquisition and interpretation capability. These requirements include a) computer controlled, automatic data acquisition, b) direct data input into the resistivity interpretation program, c) automatic interpretation option, and d) equivalence analysis capabilities. The data acquisition system will include a multi-conductor sounding cable and electrode switch box which provides a fast method for data collection. Several resistivity interpretation programs are evaluated based on the requirements stated above plus

(continued)

14. SUBJECT TERMS
Geophysics
Resistivity, Geoelectrical
Resistivity Inversion

15. NUMBER OF PAGES
83

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		

13. (continued)

other desirable features. Both theoretical and actual field data are used to evaluate the performance of each interpretation program. The program RESIX PLUS, written by INTERPLEX Ltd., Golden, Colorado, performed well and satisfies the majority of requirements.

PREFACE

The work documented in this report was performed during the period October 1991 through May 1992, and was sponsored by the US Army Corps of Engineers (USACE), Project AT40, Task WS, Work Unit 001, "Subsurface Water Location." The USACE Technical Monitor was Dr. Donald Leverenz.

The work was performed by Drs. Janet E. Simms and Dwain K. Butler, Earthquake Engineering and Geosciences Division (EEGD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES). This report was prepared by Dr. Simms. General supervision was provided by Mr. Joseph R. Curro, Chief, Engineering Geophysics Branch, EEGD, Dr. Arley G. Franklin, Chief, EEGD, and Dr. William F. Marcuson III, Director, GL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CONVERSION FACTORS, NON SI-TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres

Assessment and Selection of an Automated Electrical Resistivity Interpretation Procedure

PART I: INTRODUCTION

Background

1. The Defense Science Board and Joint Chiefs of Staff have identified ground-water supply development capability (which includes detection) as a major technological shortfall. In many areas of the world, particularly the hot, dry desert regions, existing developed water sources are nonexistent or insufficient to meet military requirements. The goal of research and development under the Corps of Engineers Water Supply Program is to provide the military with the capability to detect new ground-water sources to support operations, aid in humanitarian relief programs, and as a part of nation assistance.

Detection versus Exploration

2. Geophysical methods are routinely used throughout the world in civilian exploration programs for the assessment and development of ground-water resources. These exploration programs are far different from exploration in the military environment because there is a nearly unlimited amount of time available, there is no competition for available logistic support, and the scientific skill and experience levels of the explorers are much higher than can reasonably be expected to be available in a combat theater. The surface geophysical methods that are predominantly used in these ground-water exploration programs are gravity, electrical resistivity, electromagnetic, and seismic refraction methods. Although occasionally only one of these methods will be used in an exploration program, generally at least two of the methods are used in a complementary approach. A geophysical ground-water exploration program will normally use all available geological and borehole data in order to produce the best possible assessment of the ground-water potential and conditions in an area (Butler and Llopis 1984).

3. The primary objective of geophysical ground-water exploration is the

mapping of subsurface structural and stratigraphic indicators of the possible occurrence of ground water, such as buried river channels, fracture zones in bedrock, confining layers (aquacludes), etc. Actual detection of the ground-water table with any of the geophysical surveys may be noted but may not be of primary importance in the overall ground-water exploration assessment.

4. The expression "ground-water detection", in contrast to ground-water exploration, applies to the concept of actually detecting the presence (or absence) of ground water and the depth to the water table beneath a given "point" on the surface by conducting one or more types of geophysical tests at that point. Ideally, aquifer thickness and water quality would also be determined. For some cases, information regarding ground-water occurrence and other geological factors might be available but, in general, the assessment of the presence of ground water must rely solely on the geophysical results at the given surface location in the detection scenario. However, it is envisioned that many geophysical ground-water surveys will be conducted to aid in choosing between alternate sites in an area already identified as having good ground-water potential by other methods. Of the geophysical methods most commonly used in ground-water <u>exploration</u> programs, only electrical resistivity, electromagnetic, and seismic refraction methods are applicable to the ground-water <u>detection</u> problem. These methods are complimentary for locating possible ground-water sources, with the electrical techniques identifying different layers and variations in water salinity based on the resistivity (or conductivity) of the subsurface materials, whereas seismic data yields the subsurface structure, layer thickness, and layer velocities. Water saturated earth material has a characteristic velocity (~1500 m/s) and range of resistivities (10-300 Ω-m), therefore by combining the results obtained from the electrical and seismic methods, it is possible to determine if a ground-water source is present. Detection principles for these methods are described in Appendix A. The capabilities provided will be general enough to perform in a "detection" mode for a tactical application, or in an "exploration" mode for either fixed base water supply or humanitarian relief/nation assistance applications.

Scope

5. Initially, the detection of ground-water sources in a military environment will be achieved through an integrated, automatic data acquisition and interpretation capability for electrical resistivity and seismic refraction data. This will relieve the need for extreme levels of civilian scientific skill and experience, and also accommodate the military time constraints. The final capability is also likely to incorporate electromagnetic methods also. The second part of this report describes the design considerations for an integrated data acquisition system.

6. Prior to integrating the geophysical data sets, it is first necessary to evaluate each geophysical method independently to determine the optimum method for data acquisition and interpretation. The third part of this report addresses the electrical resistivity interpretation process. It discusses the features desirable in a resistivity interpretation program and evaluates several inversion programs based on these requirements.

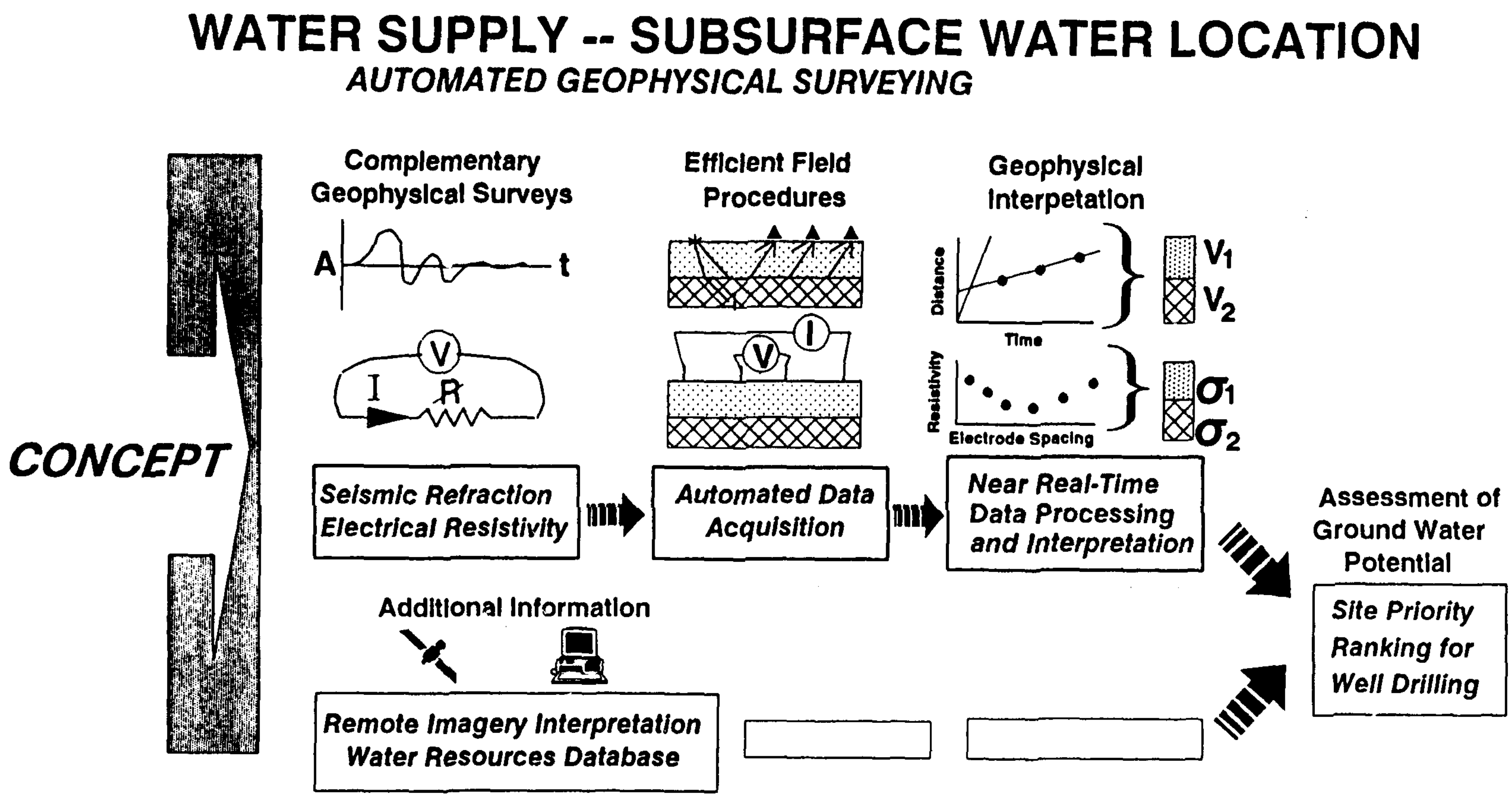


Figure 1. Conceptual diagram of automated geophysical surveying capability.

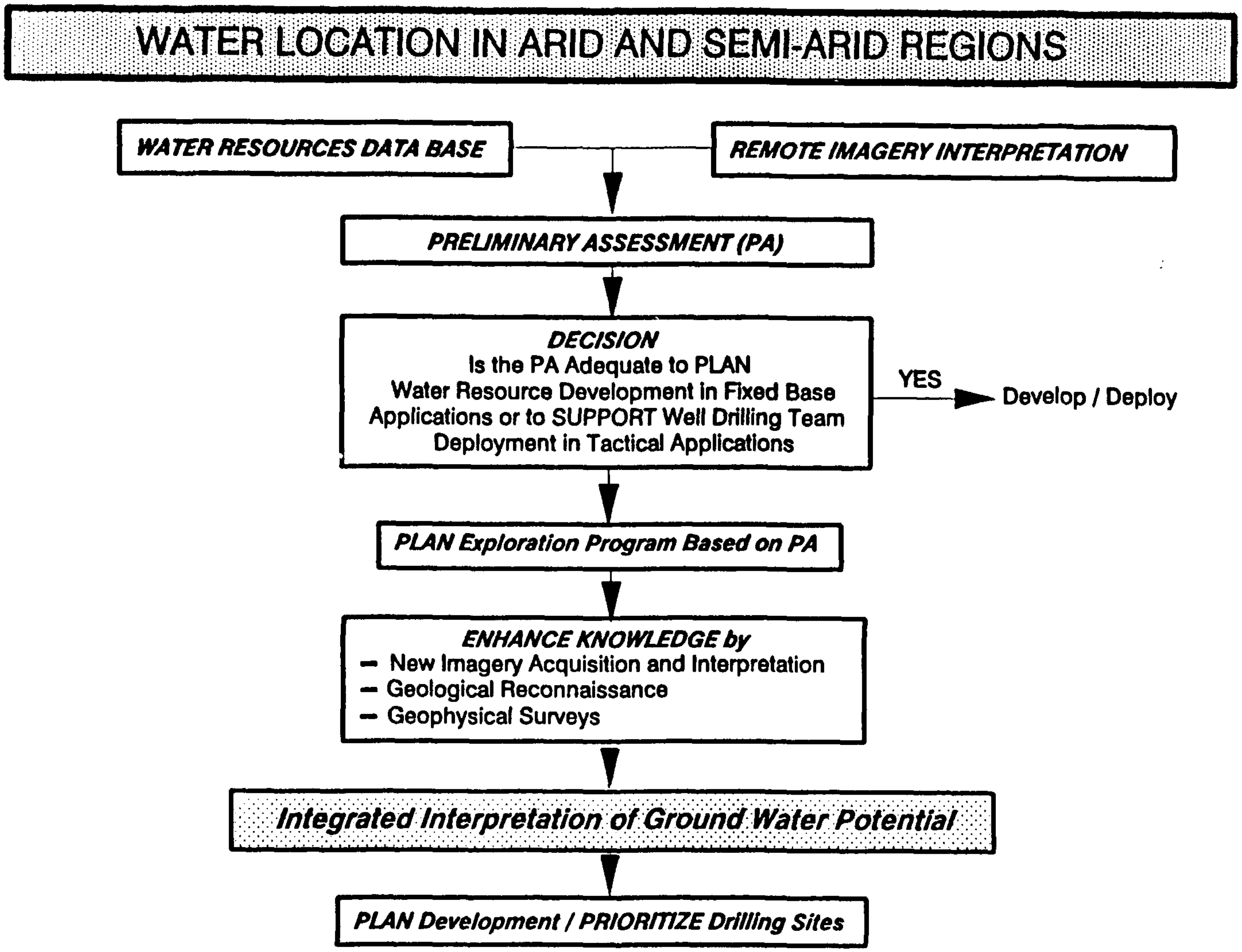


Figure 2. Flow chart showing steps involved in the implementation of the automated geophysical surveying capability.

--climate

e) drilling rig capability

--drilling method

--depth limitations

f) logistical considerations

--location/operational requirements

--accessibility/mobility

--security

--estimated drilling time

8. Desired features of the resistivity and seismic refraction data acquisition and interpretation capability are summarized in Figure 3. The data acquisition systems for both the resistivity and seismic methods are described below, with the remaining sections of this report concentrating on the resistivity interpretation aspects.

Seismic Data Acquisition Capability

9. The seismic refraction data will be acquired using conventional methods with the addition of computer controlled acquisition (Figure 4). The system consists of a 24 channel seismograph with roll-along data acquisition capability. A typical geophone cable consists of twelve geophones, with geophone spacings available from 10 feet to 50 feet (ft) (total cable length 120-600 ft). The length of the seismic line is dependent on the desired depth of investigation, generally 4 to 5 times the depth of investigation. For drilling rig capabilities of 600 ft and 1500 ft, the minimum length of a seismic line would be 2400 ft and 6000 ft, respectively. The knowledge assisted system will guide the user through the setup of acquisition parameters and the data collection procedure. The data will be exported directly to an external computer for interpretation using the seismic refraction data processing software SEISMO (Yule and Sharp, 1990). SEISMO is an interactive program which determines the velocity structure based on a given set of travel times. At the present time, the program requires the input of an apparent velocity model in order to obtain the true velocity profile. The apparent velocity model can be entered in one of two ways: 1) the model can be entered via keyboard, or 2) the model can be obtained interactively by

WATER LOCATION IN ARID AND SEMI-ARID REGIONS

DESIRED FEATURES -- AUTOMATED GEOPHYSICAL DATA ACQUISITION/INTERPRETATION CAPABILITY

RESISTIVITY

Multielectrode Sounding Cable

Knowledge-Assisted, Optimized Field Procedure

Automated Current and Potential Electrode Switching

Automated Processing to Produce "Real-Time" Apparent Resistivity vs. Electrode Spacing Curve for Data Quality Assessment

Decision: - Automated Interpretation (Inversion)
- User-Input Initial Model

Display Data, Best Fit Model Curve, Fit Statistics

Display Interpretation (Model)

Decision: - Single / Spot sounding
- Profile of Soundings

For Profile of Soundings, Display Depth Section and/or Pseudo-Section

Save Model for Hydrogeological Interpretation Phase

SEISMIC REFRACTION

Optimized 24-Channel Cable, Possibly with Roll-Along Capability

Knowledge-Assisted, Optimized Field Procedure

Automated Data Storage and Shot Point Sequencing

Decision: - Automated First Arrival Detection
- Manual First Arrival Picking

Automated Display of Arrival Time vs. Distance Data

Decision: - Automated "No. of Layers" Selection
- User Selected "No. of Layers"

Automated Least squares Fits to Determine Apparent Velocities and Intercept Times

Automated Interpretation to Give True Velocities and Layer Thicknesses

Option to Perform Delay Time or Generalized Reciprocal Method Analyses

Graphical display of Interpreted Model

Save Model for Hydrogeological Interpretation Phase

Figure 3. Desired features of the automated geophysical surveying capability.

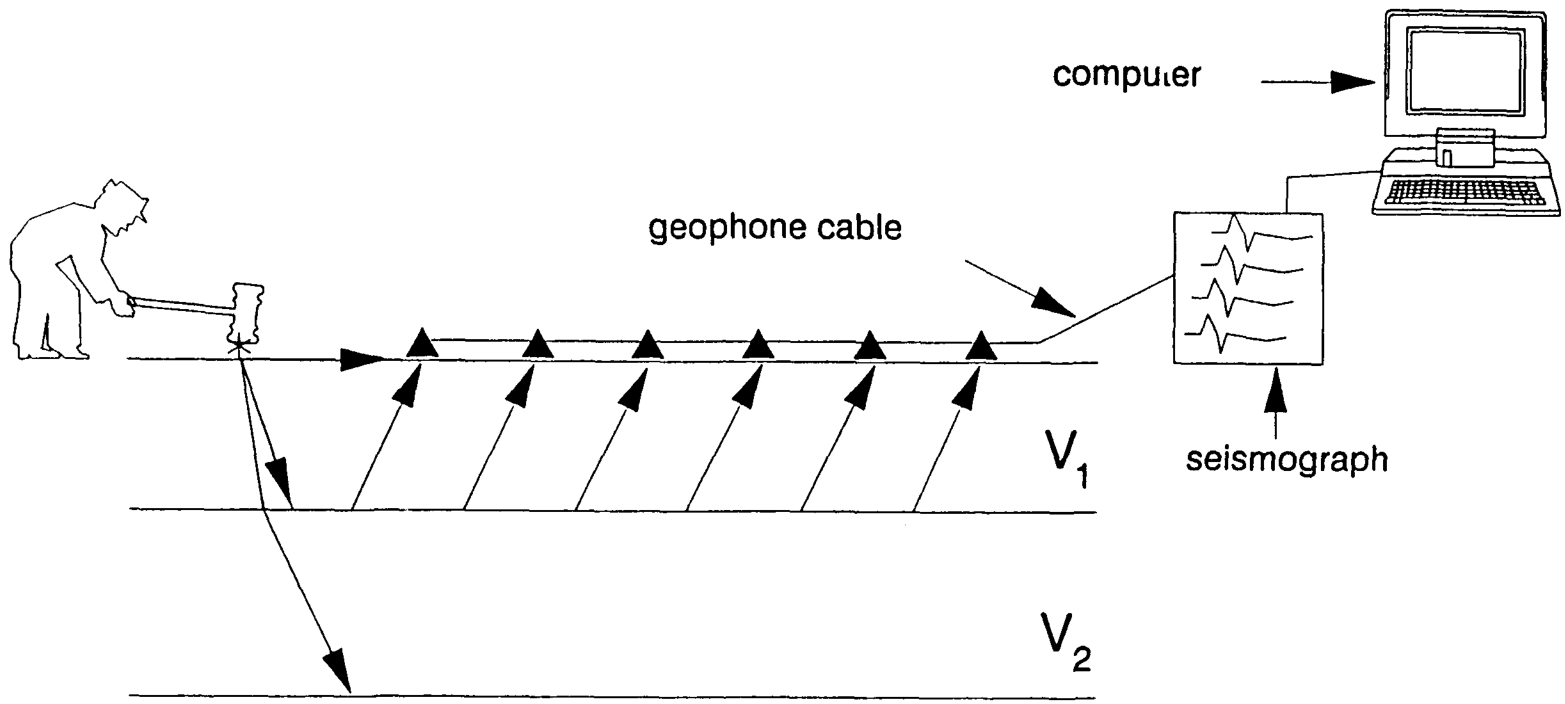


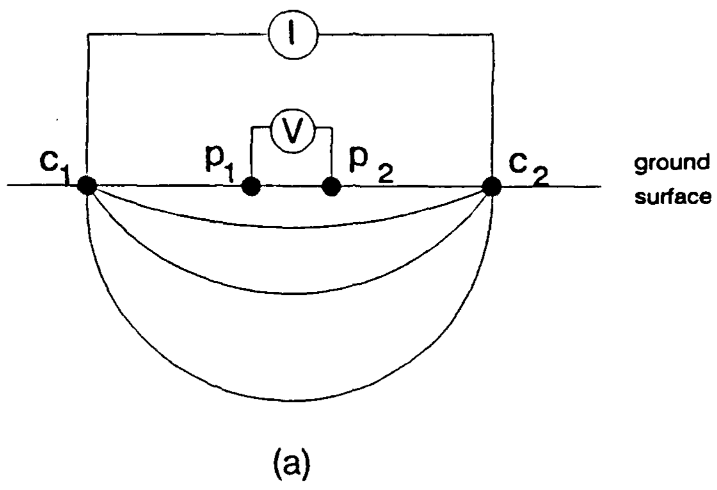
Figure 4. Seismic refraction data acquisition system.

identifying points where the slope in the travel time versus distance curve changes. There are plans to make this step optional (where the user aids in determining the initial model) and allow for the program to be completely automatic.

Resistivity Data Acquisition Capability

10. The conventional method for collecting d.c. resistivity data is to use four electrodes, two current electrodes (C) and two potential electrodes (P), placed in a straight line (Figure 5a). The spacing between the electrodes is dependent on the type of array used and the desired depth of investigation. A general rule of thumb is that the maximum current electrode spacing should be 3 to 5 times the desired depth of investigation. Current is injected into the ground through one current electrode and returns through the other. The potential difference measured between the two potential electrodes can be related to the resistivity of the subsurface material (refer to Engineer Manual 1979). Several measurements are required to construct one sounding curve. Each measurement is taken at a different electrode spacing, requiring the electrodes to be moved after every measurement. This requires extra manpower and is a time consuming process.

11. In the au omated data collection system, the electrodes are placed at each desired spacing and connected to a multi-conductor sounding cable, using an electrode clip lead, prior to taking any measurements (Figure 5b). The multi-conductor cable is connected to an electrode switching box which allows a quick method for either manual or automatic (via computer) switching of electrodes. This reduces the manpower requirements and data acquisition time for performing a resistivity survey. The electrode switch box is connected to the resistivity instrument, which is powered by a 12 volt battery. The system will allow data collection to be computer controlled or manually controlled through the resistivity instrument. If computer controlled, the program will prompt the user for array type, maximum electrode spacing, and other information necessary to perform the survey. The data are input directly into the computer as it is collected. The program will prompt the user to either accept the measurements or remeasure to ensure good quality data. Upon completion of the survey, the resistivity interpretation program is



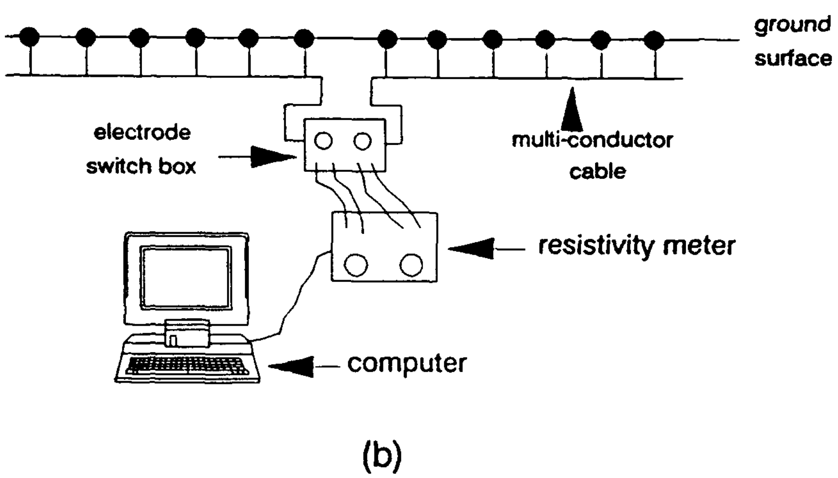


Figure 5. Resistivity data acquisition system. (a) conventional method and (b) automated system.

activated and, either automatically or user assisted, the data inverted to obtain the number of (electrical) layers present and the resistivity and thickness of each layer. This information will be combined with the results from the seismic refraction survey to determine if the local site is a potential ground-water source.

PART III: DESIRABLE ATTRIBUTES OF RESISTIVITY INTERPRETATION

12. The following discussion addresses the features desirable in a resistivity interpretation program. Parts IV and V evaluate several inversion programs based on these requirements. The resistivity inversion programs are evaluated based on the following features: 1) how robust is the inversion algorithm, 2) ability for direct data input, 3) automatic interpretation capabilities, 4) equivalence analysis, 5) graphical output, 6) how user-friendly is the program, and 7) ease of incorporating the program into the overall multi-interpretation capability.

Inversion Algorithm

13. The inversion algorithm is the core of any resistivity interpretation program and it is necessary that it be robust. Noise will always be present in any resistivity data set, therefore the algorithm must adequately handle the noise and any problems encountered due to the inherent nonuniqueness of resistivity data. The need for a robust algorithm is evident when one considers the possibility that a nonrobust algorithm can invert a set of data which has a unique solution and converge to the wrong solution. The primary criteria for evaluating a resistivity interpretation program should be the robustness of the inversion algorithm.

14. The inversion algorithm should also have the capability to handle Schlumberger, Wenner, and dipole-dipole array data. These three array types allow the versatility to collect sounding or profiling data with various depths of investigation.

Direct Data Input

15. The data should be directly imported into the resistivity inversion program from the data acquisition system. This would eliminate errors which may arise from manually inputting the data and reduce the time required for interpreting the data. If a commercially available inversion program is used, then the software company must be willing to either supply the program source

code or adapt the program to satisfy this requirement.

Automatic Interpretation

16. The ultimate user of the data acquisition and interpretation system will be military personnel with no formal training in or knowledge of geophysics. Since the system is geared toward the layman, it is highly desirable to have the option of automatic data interpretation. This option will automatically generate the required initial model for input into the inversion program. Since the automatic interpretation option may generate an initial model having similar adjacent layer resistivities or layers that are too thin to be resolved at depth, it is recommended that a model integrity routine be run following the formation of the initial model. Suggested criteria are: (i) the thickness of a layer should be a minimum of 20% of the total thickness of the layers above it; (ii) the resistivity of a layer should differ from the layer immediately above it by more than 35%; and (iii) the fitting error of the smoothed model should be within 10% of the fitting error obtained with the unsmoothed model. These criteria will ensure that the initial model consists only of layers that are significant for fitting the data. None of the resistivity interpretation programs evaluated have this feature, though it would be easy to incorporate.

17. Caution must be exercised when using the automatic interpretation option to avoid pitfalls encountered when the human factor is removed from the decision process. It is recommended that the user have at least minimal training in the interpretation process. The traditional method of the user supplying the initial model will also be available as an option.

Equivalence Analysis

18. Resistivity data is inherently nonunique, therefore an inversion program should include a routine which performs equivalence analysis. Equivalence analysis gives the range of variation in the parameters which will fit the data within a specified error bound. The range of variation in a parameter is a measure of the resolution of the parameter, with a smaller range of variation indicating better resolution. Also, knowing the range of

parameter variation could aid in identifying the soil or rock type.

Graphical Output

19. The resistivity inversion program should provide on-screen and hard copy plots of the data, best-fit sounding curve, inversion model, and range of equivalent solutions. The program should also provide a tabular listing of the data and inversion results.

User-Friendly Program

20. A user-friendly inversion program is a necessity since it will be used by individuals who may not have the time to become familiar with the intricacies of the program. It should guide the user through the interpretation process, preferably through menus, with the possibility of being fully automatic. If a commercially available program is used, aid from the software company in meeting these requirements may be required.

Incorporation Into Overall System

21. The resistivity inversion program must be compatible with the entire data acquisition and interpretation capability (resistivity, seismic, etc.). A UNIX operating system is desired which will give compatibility (interfacing capability) with the TERRACAMMS data base and geographical information system, and other logistics planning tools (Falls et al. 1991). Willingness of the software company to aid in meeting the compatibility requirements would be advantageous.

PART IV: SURVEY OF AVAILABLE RESISTIVITY INTERPRETATION PROGRAMS

22. Five resistivity interpretation programs are compared. Two of the programs, RESINV and ATO, are available through government publications and the other three, DCRESI, RESIX, and SVES, are commercially available. Each program is evaluated based on the features described in Part III, with the inversion algorithms evaluated in Part V. The programs and their features are listed in Table 1 for reference.

DCRESI

23. DCRESI is no longer commercially available but has been replaced by RESIX, which is written and distributed by INTERPEX Ltd., located in Golden, Colorado. The U.S. Army Engineer Waterways Experiment Station (WES) possesses a copy of DCRESI. The program is not user-friendly. It is a command driven program, as opposed to menu driven, and the user must be familiar with the program in order to execute the commands in the proper sequence. DCRESI supports several electrode array types but it does not have an option for automatic interpretation or equivalence analysis. The program does meet the minimum graphical output requirements. It cannot run on a UNIX platform. Data cannot be directly imported into the program and, since DCRESI is no longer in distribution, the software company is not favorable to amending it to meet our requirements. Therefore, the program DCRESI will not fit well into the overall capability.

RESIX

24. The program RESIX PLUS is the revised version of DCRESI. It is menu driven which makes the program more user friendly. The program can model data collected from several electrode array configurations, and has options for automatic interpretation and equivalence analysis. At the present time, the data cannot be automatically read into the program via the resistivity meter, but the software company, INTERPEX Ltd., is willing to modify the program to meet our needs. Personnel at the WES can also provide this service. INTERPEX

Table 1

Features of Resistivity Interpretation Programs

	PROGRAMS			
Feature	DCRESI	RESINV	SVES	RESIXPLUS
user-friendly			yes	yes
graphic output	yes	yes	yes	yes
direct data input			yes	
various electrode arrays	yes	yes		yes
automatic interpretation			yes	yes
equivalence analysis			yes	yes
unix platform		yes		yes
easily incorporated				yes

DCRESI and RESIX PLUS: INTERPEX, Ltd., Golden, Colorado.

SVES: Atlas Copco ABEM, Bromma, Sweden

RESINV: Butler et al. (1982), Davis (1979a, b), Mooney (1979)

is currently adapting the program to run on a UNIX platform. RESIX PLUS would fulfill our resistivity interpretation requirements. The WES possesses a copy of RESIX PLUS.

SVES

25. SVES was written by the Swedish company Atlas Copco ABEM for use with their resistivity instrument, the Terrameter. The data (Schlumberger array only) can be imported directly into the resistivity inversion program SVES when used in conjunction with the GEOMAC (ABEM trademark) hand-held computer and Terrameter. The program has an automatic interpretation option but does not offer an equivalence analysis routine. It is menu driven, relatively user-friendly, and satisfies the graphical output requirements. SVES runs on a DOS platform and there are no plans to modify it to run on a UNIX platform. SVES has problems running under DOS 5.0. ABEM recently announced that they will support the INTERPEX resistivity interpretation software, therefore support or future upgrades to SVES will be limited or non-existent. Because of the limited support for SVES, it is not recommended that SVES be used in the Water Supply Program. WES does possess a copy of the program SVES.

RESINV

26. The program RESINV is available through government publication (Butler et al. 1982, Davis 1979a, b, Mooney 1979). It is written in Fortran and will run on a UNIX system. The program is neither menu or command driven, but runs through a complete interpretation of the data without pausing at intermediate steps waiting for user input. It could be modified to run in a menu driven mode. In its present state, it does not offer automatic interpretation or equivalence analysis options but WES personnel could write these routines. The program will accept either Schlumberger, Wenner, or dipole-dipole data. RESINV could be modified to accept data input directly from the resistivity meter. With the above changes, program RESINV could satisfy our requirements. These changes, however, would require a considerable amount of time to incorporate.

ATO

27. Resistivity inversion program ATO is also available through a government publication (Zohdy and Bisdorf 1989). It can only be used to model Schlumberger data. The program is a type of direct interpretation program in that it does not require an initial model, but fits a model consisting of as many layers (N) as there are data points (M, i.e., $N=M$). This violates the general principles of nonlinear inversion, where typically $N<M$ or even $N \ll M$. The resulting model shows more of a continuous variation in resistivity with depth rather than a discrete layer structure. This type of resistivity interpretation is not readily amenable to joint interpretation with other methods which result in a layered structure. Therefore the program ATO will not be given further consideration.

PART V: EVALUATION OF RESISTIVITY INTERPRETATION PROGRAMS

28. Resistivity interpretation involves determining the number of subsurface layers represented by the sounding data and the resistivity and thickness of each layer. Prior to the advent of computers, all resistivity interpretation was done using a set of master curves (Orellana and Mooney 1966). These curves represent simple two and three layer models, and by matching the field sounding curve with the appropriate master curve it is possible to determine the number of layers present and the resistivity and thickness of each layer. As the popularity, capabilities, and availability of computers grew, methods were developed which computerized the curve matching process.

29. All interpretation programs evaluated here utilize a nonlinear least-squares inversion scheme (Marquardt 1963, Inman 1975). Generally, a resistivity interpretation program requires input of field data (actual or theoretical), the number of model layers, and an initial estimate or guess of the resistivity and thickness of each layer. The layer parameters are usually estimated based on the shape of the sounding curve. Using the initial guess of the layer parameters, a set of data is generated which is compared to the field data. Through an iterative process, the inversion algorithm minimizes the root mean square error between the field data and generated data, updating the parameters until a given error criterion is satisfied. The automatic interpretation programs do not require an initial guess of the layer parameters, but instead use a computer algorithm (Koefoed 1976) to generate the initial model.

30. Both theoretical and actual field data are used to evaluate the resistivity inversion algorithms. Theoretical data are used because the solution is known, whereas with field data the results can only be corroborated with other types of field data, if available. Five percent Gaussian noise is added to the theoretical data to simulate field conditions. The theoretical examples range from simple three layer models which can be well resolved through the inversion process, to models which exhibit both nonuniqueness and poor resolution. Five of the real field data examples are from an arid or semi-arid region. These examples were chosen because it is

important to see how the various algorithms respond to different types of data. The four theoretical examples are discussed first, followed by the seven field examples. It should be noted that, for the inversion programs which require an initial model, the same initial model was used in each program for a given example.

Theoretical Examples

Example 1

31. The first theoretical example consists of three layers, with the second layer being conductive. The true model and corresponding sounding curve are given in Figure 6. This example can be considered relatively unique and therefore the inversion algorithms should have no problem in resolving the true parameter values and the range of equivalent solutions should be small.

32. The programs DCRESI, RESINV, and the user-aided (initial model provided by the user) SVES and RESIX programs do well in fitting the true parameter values, all obtaining very similar solutions (Figure 7a). The automatic interpretation of SVES fails to achieve a suitable inversion model (unable to plot at the scale of Figure 7b). The RESIX automatic interpretation yields a five-layer model when smoothing is not applied. If the initial model estimate is smoothed prior to inverting the data using the criteria discussed in Part III, then the resulting model is identical to the user-aided RESIX inversion model (Figure 7b).

Example 2

33. Example 2 also consists of three layers but now the second layer resistivity has a value of ρ_2=100Ω-m, making the model highly nonunique (Figure 8). The algorithms are not expected to perform well in resolving the second layer parameters, so there should be a large range of parameter values which can fit the data within a small specified error.

34. The inversion results are given in Figure 9. Program DCRESI does surprisingly well in estimating the true layer parameters for this nonunique model. Unfortunately it does not have an equivalence analysis routine. The

EXAMPLE 1

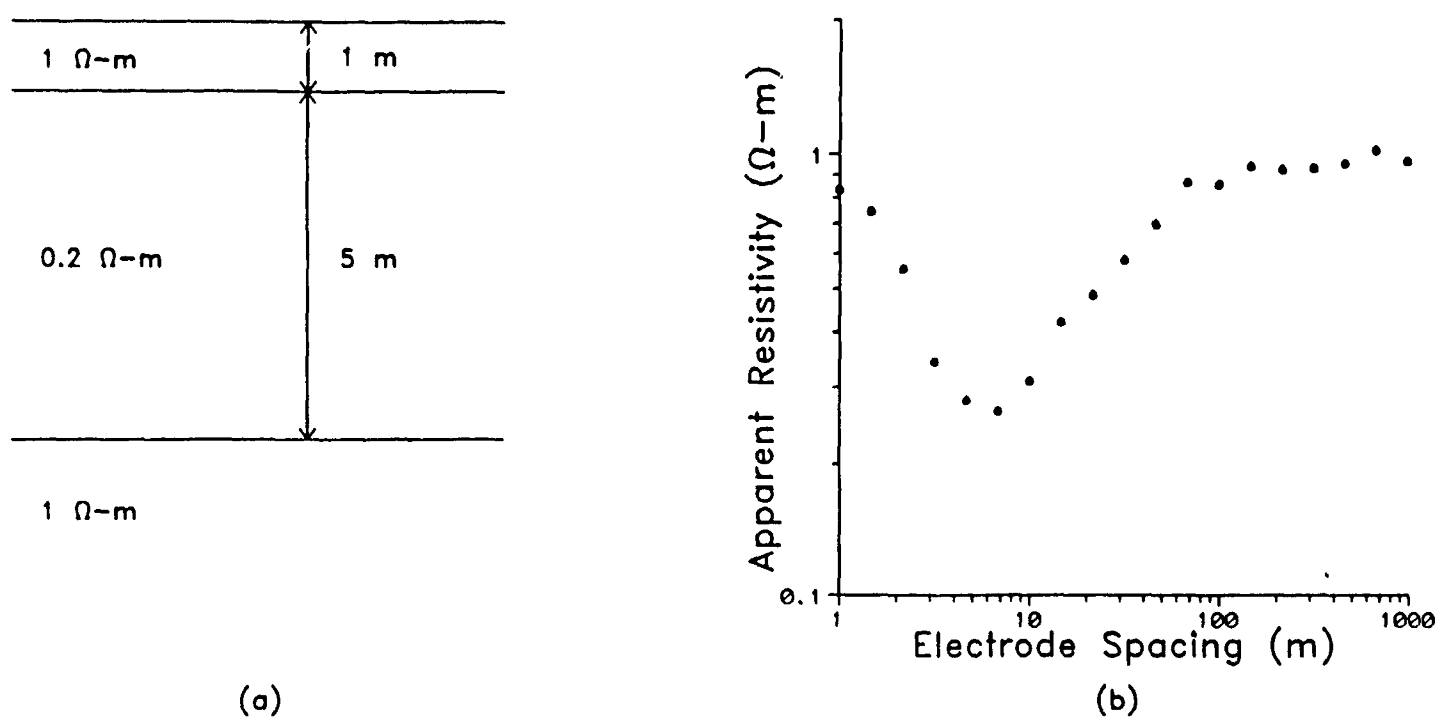


Figure 6. Example 1, (a) three-layer model and (b) corresponding theoretical Schlumberger sounding curve with 5% Gaussian noise added.

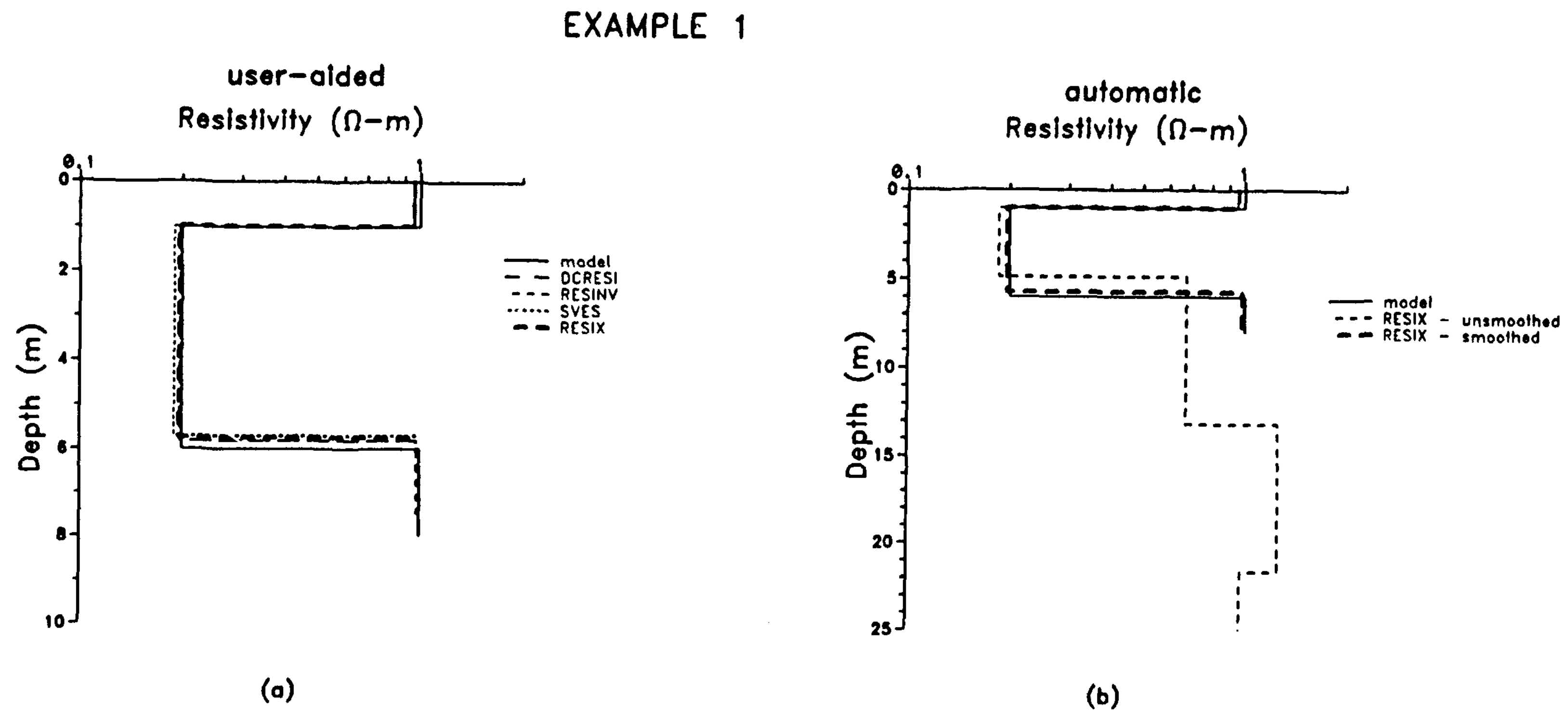


Figure 7. Example 1, inversion results using the (a) user-aided and (b) automatic interpretation methods.

EXAMPLE 2

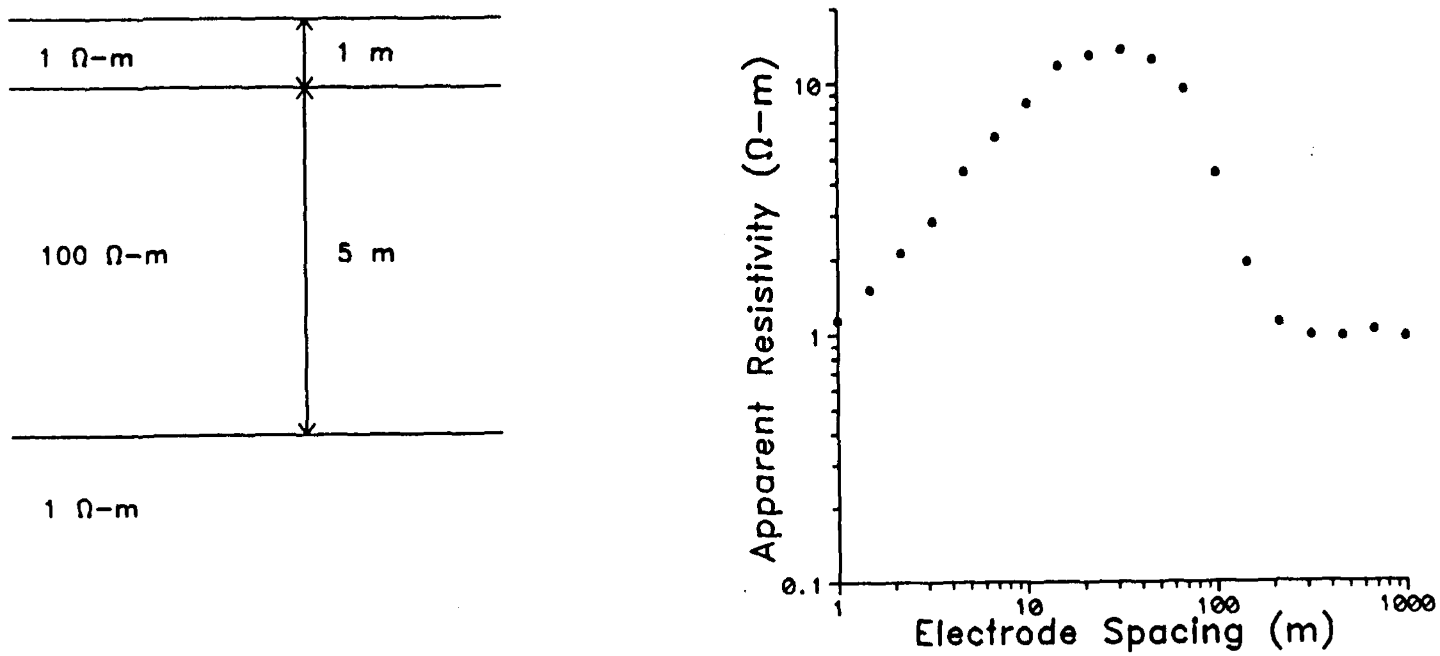


Figure 8. Example 2, (a) three-layer model and (b) corresponding theoretical Schlumberger sounding curve with 5% Gaussian noise added.

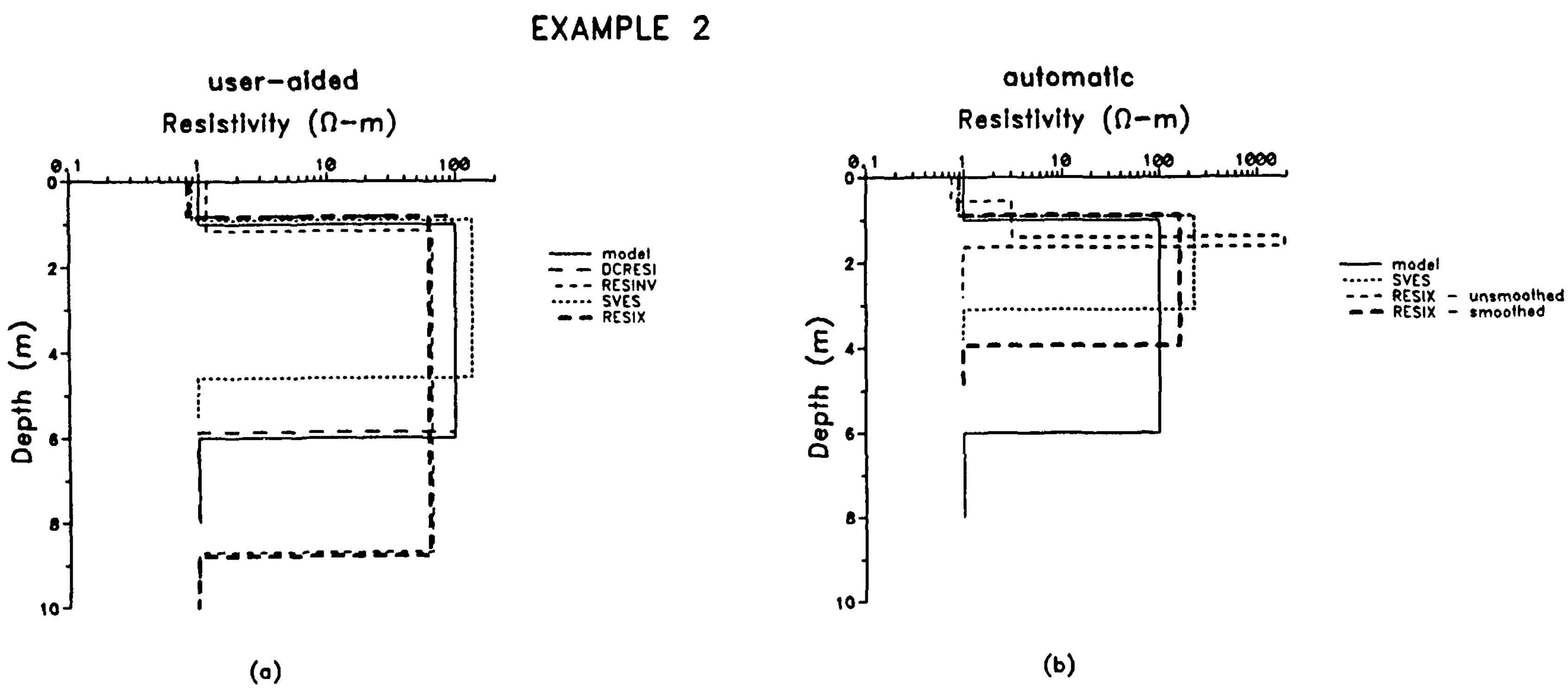


Figure 9. Example 2, inversion results using the (a) user-aided and (b) automatic interpretation methods.

user-aided and automatic SVES inversion results are similar, both overestimating the second layer resistivity and underestimating the thickness. Programs RESINV and user-aided RESIX also obtain similar results, but they underestimate the resistivity and overestimate the thickness of the second layer. Nonuniqueness is affecting these parameters. The automatic model estimate of RESIX initially obtains a four-layer model, but by applying smoothing criteria (i) the third layer can be eliminated (Figure 9b). This smoothed RESIX model is the best of the automatic fitting programs.

Example 3

35. The third example consists of four layers with moderate contrasts in layer resistivity (Figure 10). The parameters should be fairly well resolved through the inversion process with a bounded range of equivalent solutions. However, as the number of layers increases, the parameter resolution decreases which corresponds to an increase in equivalent solutions.

36. Again, DCRESI achieves the best inversion model (Figure 11a). RESINV and the user-aided program RESIX also result in good inversion models. Both automatic interpretation programs overestimate the number of layers in the true model (Figure 11b) (the arrow indicates that the curve extends beyond the bounds of the graph). Of the two, the six-layer model of RESIX is a better estimate. The RESIX initial model does not meet any of the smoothing criteria. However, since the additional layers have resistivity values between those of the surrounding layers, it is an acceptable model.

Example 4

37. The fourth data set is an example of poor resolution, where the data cannot resolve the presence of a thin layer or a layer having an intermediate resistivity. The four layer model consists of three layers with gradually increasing resistivities overlying a conductive basement (Figure 12). The sounding curve, however, suggests a three layer model, where the second layer with a resistivity of 10Ω-m appears invisible. The inversion algorithms probably cannot identify the presence of the hidden layer. This example will appear like Example 2, thus the second layer parameters should show a large

EXAMPLE 3

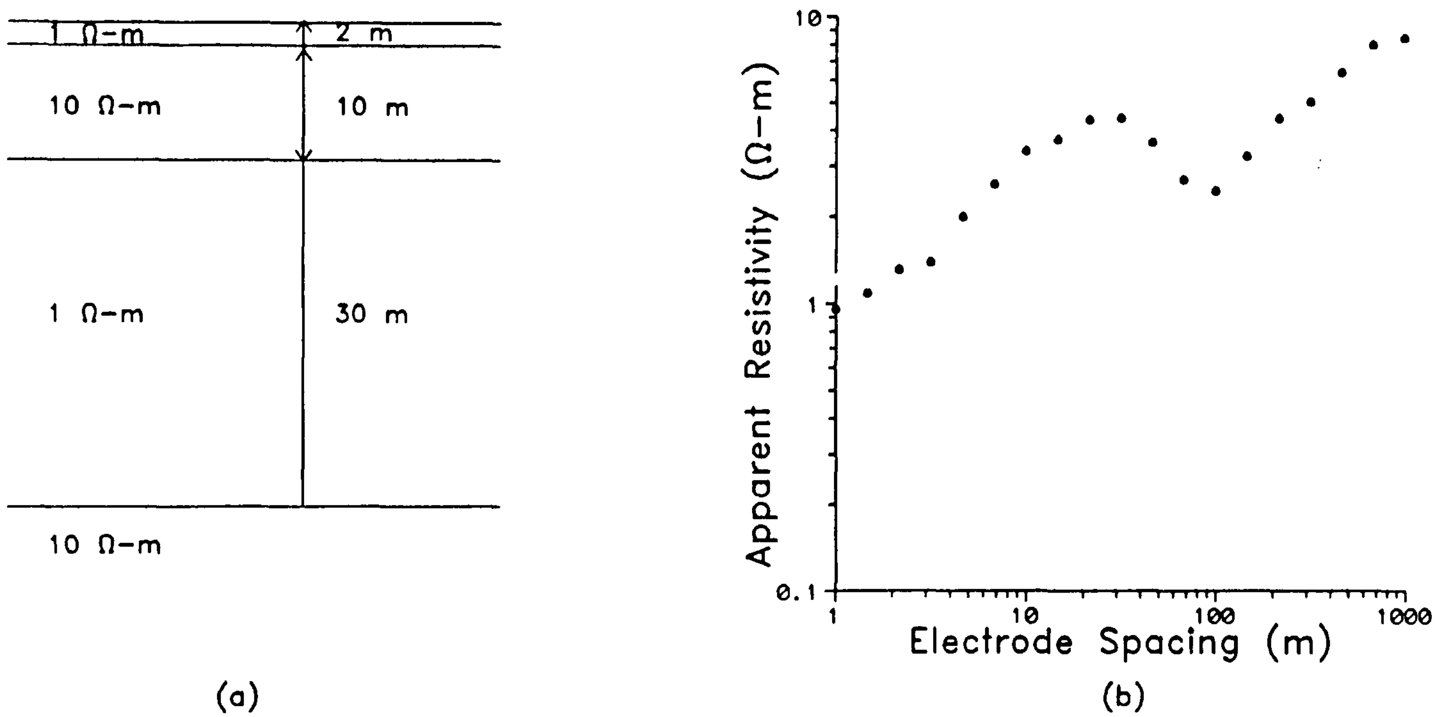


Figure 10. Example 3, (a) four-layer model and (b) corresponding theoretical Schlumberger sounding curve with 5% Gaussian noise added.

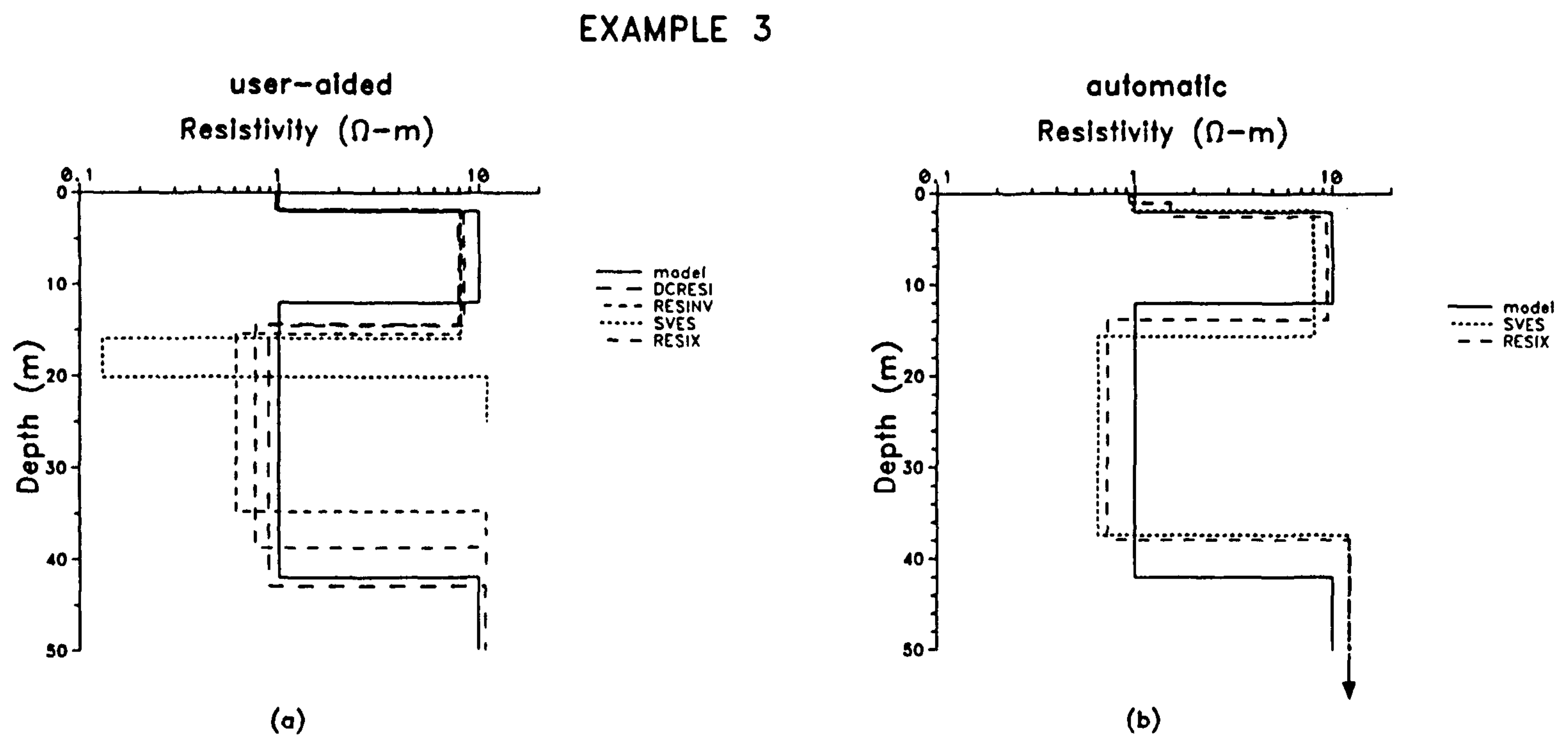
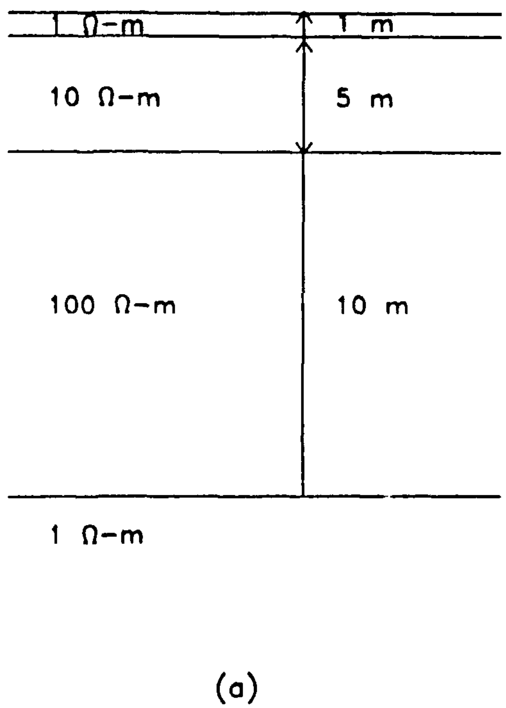


Figure 11. Example 3, inversion results using the (a) user-aided and (b) automatic interpretation methods.

EXAMPLE 4



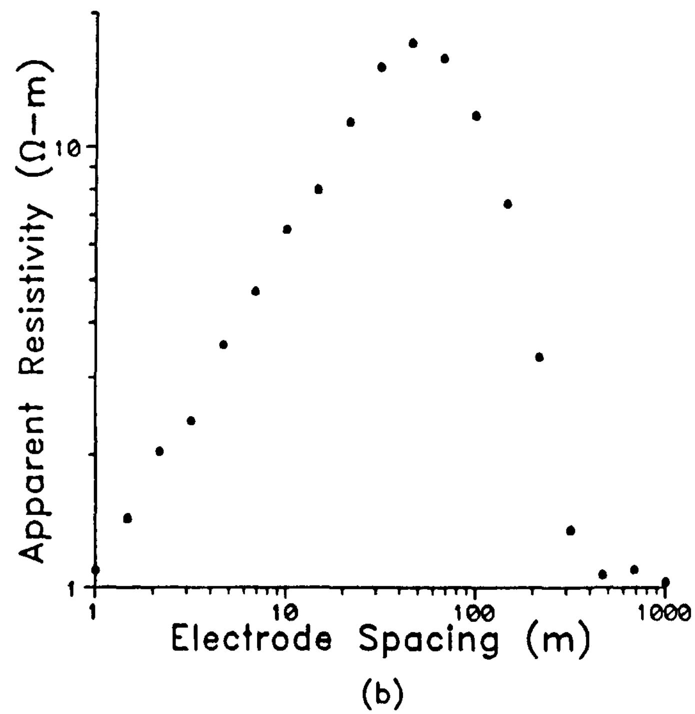


Figure 12. Example 4, (a) four-layer model and (b) corresponding theoretical Schlumberger sounding curve with 5% Gaussian noise added.

range of parameter variation which can give equivalent solutions.

38. The automatic interpretation SVES model is the only one that contains four layers, thus identifying the presence of the hidden layer (Figure 13b). The model is a good fit to the true solution. The automatic RESIX program initially obtains a six-layer model but applying pre-inversion smoothing reduces it to five layers. This inverted model is a good approximation to the known solution. The user-aided programs only identify three layers present, mainly because the initial model was inputted by the user and that initial model was based on the shape of the sounding curve, which suggests three layers. This example points out an important failure of resistivity inversion programs - they cannot <u>increase</u> the number of layers in an initial model, but only reduce them by indicating a very small layer thickness or a layer resistivity similar to that of an adjacent layer. Three of the user-aided inversion models are quite similar, although poor, while the SVES model is very bad (Figure 13a).

Field Examples

Example 5

39. The first field example is a set of data collected for the purpose of detecting possible ground-water contamination. Both seismic and resistivity data were collected at this site. The data suggest a subsurface structure consisting of three layers but a borehole indicates four layers present (Figure 14). All of the user-aided programs and one automatic program (SVES) obtain three layer models, most having similar results (Figure 15). The automatic RESIX inversion model consists of four layers. Without any other geologic information available, the automatic RESIX model is the favored interpretation. The resistivity inversion results indicate an overburden layer as does the seismic data (Figure 14c), however the seismic data identifies an intermediate interface at 52 feet whereas the resistivity models indicate a deeper bedrock interface. Using the borehole information and seismic data, the original interpreter fit a five-layer model and was able to identify the

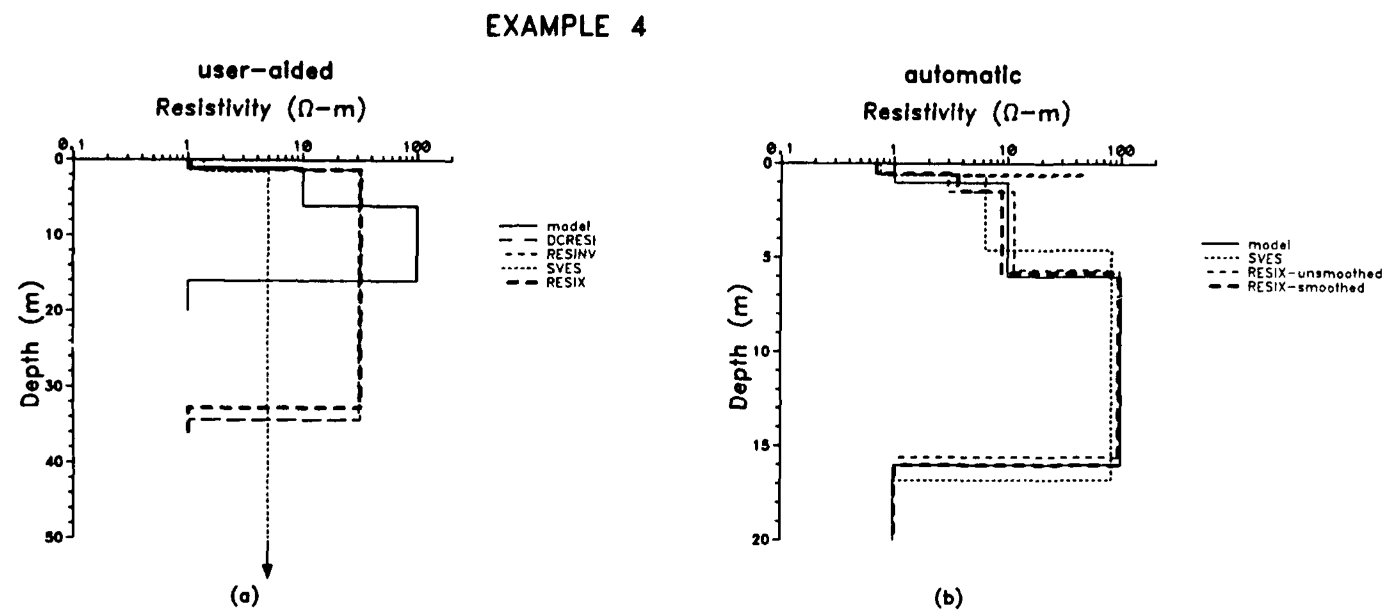


Figure 13. Example 4, inversion results using the (a) user-aided and (b) automatic interpretation methods.

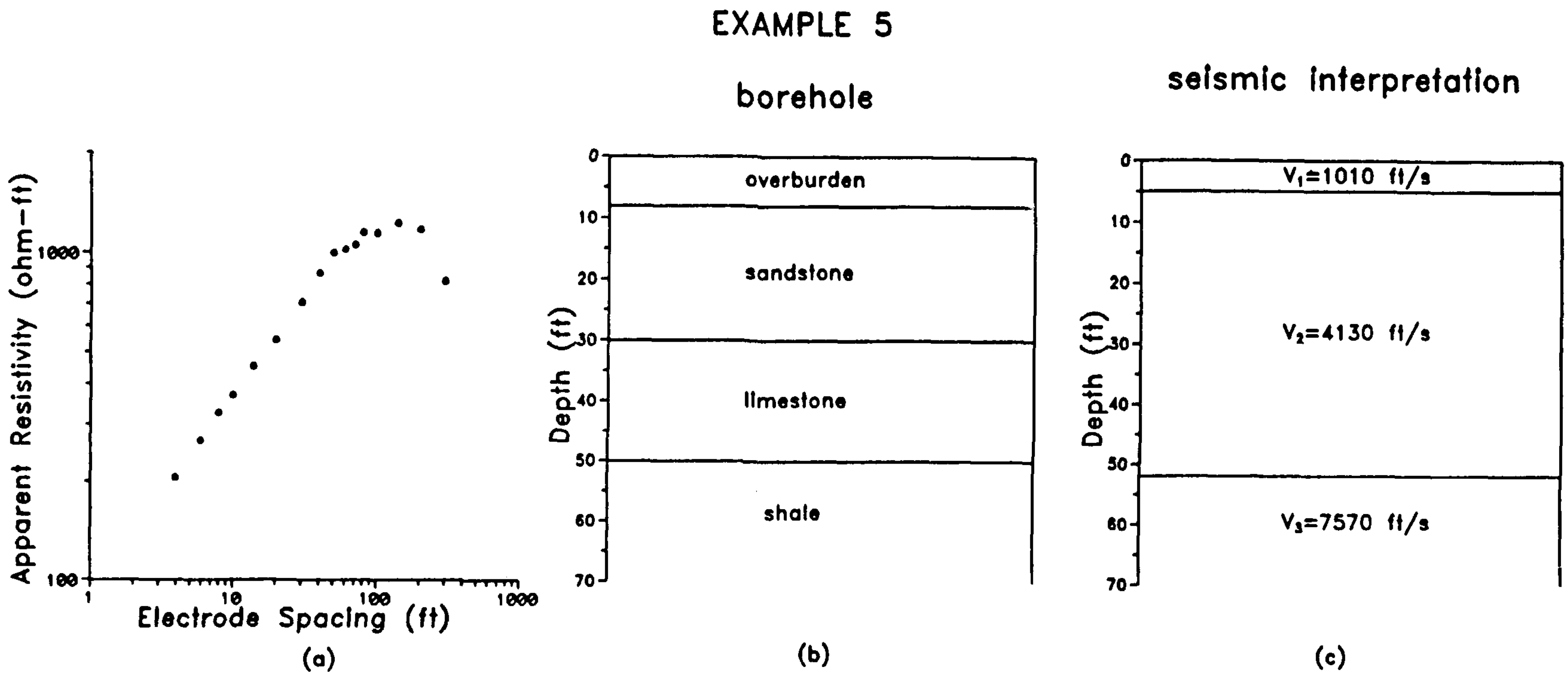


Figure 14. Example 5, (a) Schlumberger field data, (b) borehole data, and (c) seismic interpretation.

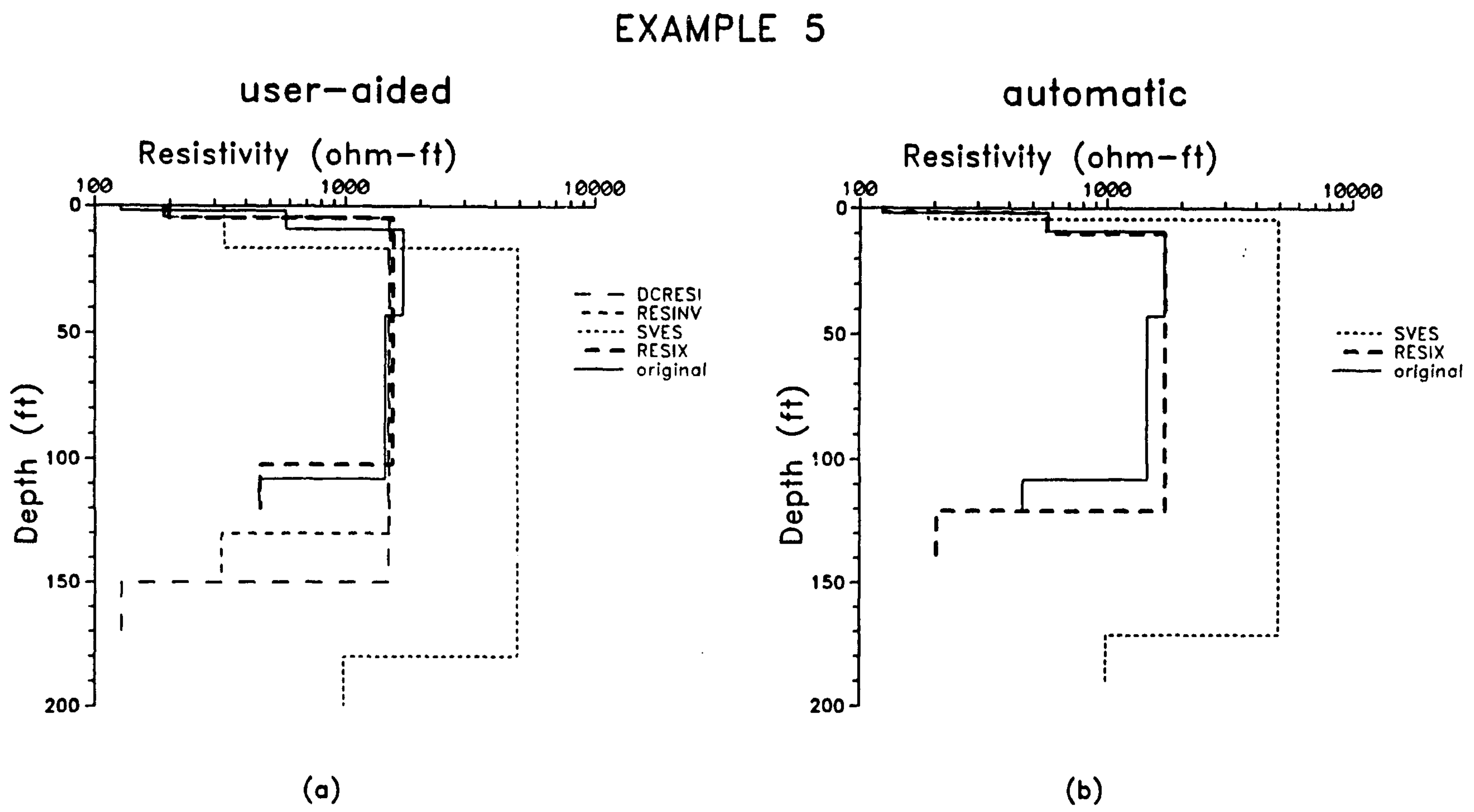


Figure 15. Example 5, inversion results using the (a) user-aided and (b) automatic interpretation methods.

intermediate layer in the resistivity data[1] (Figure 15). (For this example and the ones that follow, the curve designated as "original" is the interpretation obtained by the original interpreter). However, based on the resistivity data alone, a five-layer model is not justified.

Example 6

40. This set of data was collected at a landfill area to identify the boundaries of the landfill. The Schlumberger sounding curve suggests four or five layers present (Figure 16). For the user-aided programs, a five-layer model was used to fit the data. The resulting inversion models are fairly similar, with the major difference being the thickness of the fourth layer (Figure 17a). The model obtained using DCRESI reduces to four layers since the resistivities of the third and fourth layers do not differ by more than 1Ω-m. The automatic SVES program obtains a two-layer model which is a very poor fit to the data, whereas a good fit to the data is achieved by a five-layer model using the automatic RESIX program (Figure 17b). The original interpreter also found that a five-layer model adequately fits the data[1].

Examples 7,8

41. These two data sets are from the White Sands Missile Range in New Mexico (Butler and Llopis 1984). The region is semi-arid and the data were collected over an unconfined alluvial aquifer. Seismic and resistivity data were collected at both survey sites.

42. The first Schlumberger resistivity data set (SW-19) suggests a four layer model with the seismic data also indicating four layers (Figure 18). With the user-aided programs, a three-layer model had the smallest fitting error using programs DCRESI and SVES, while RESINV and RESIX achieved a best fit with a four-layer model (Figure 19a). The automatic fitting programs (RESIX and SVES) obtained an optimum fit with four layers (Figure 19b). When

---

[1] Personal Communication, Keith J. Sjostrom, Civil Engineer, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

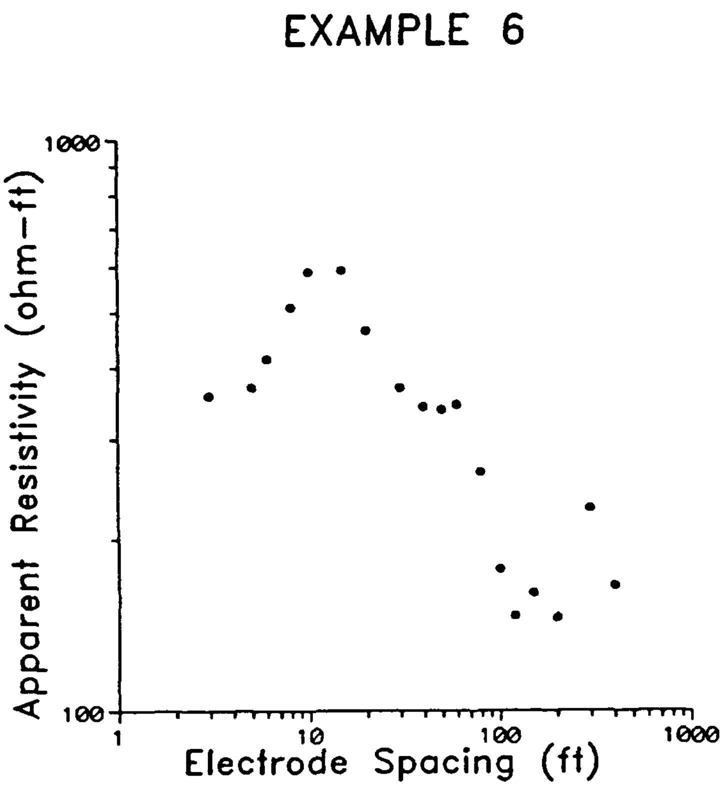
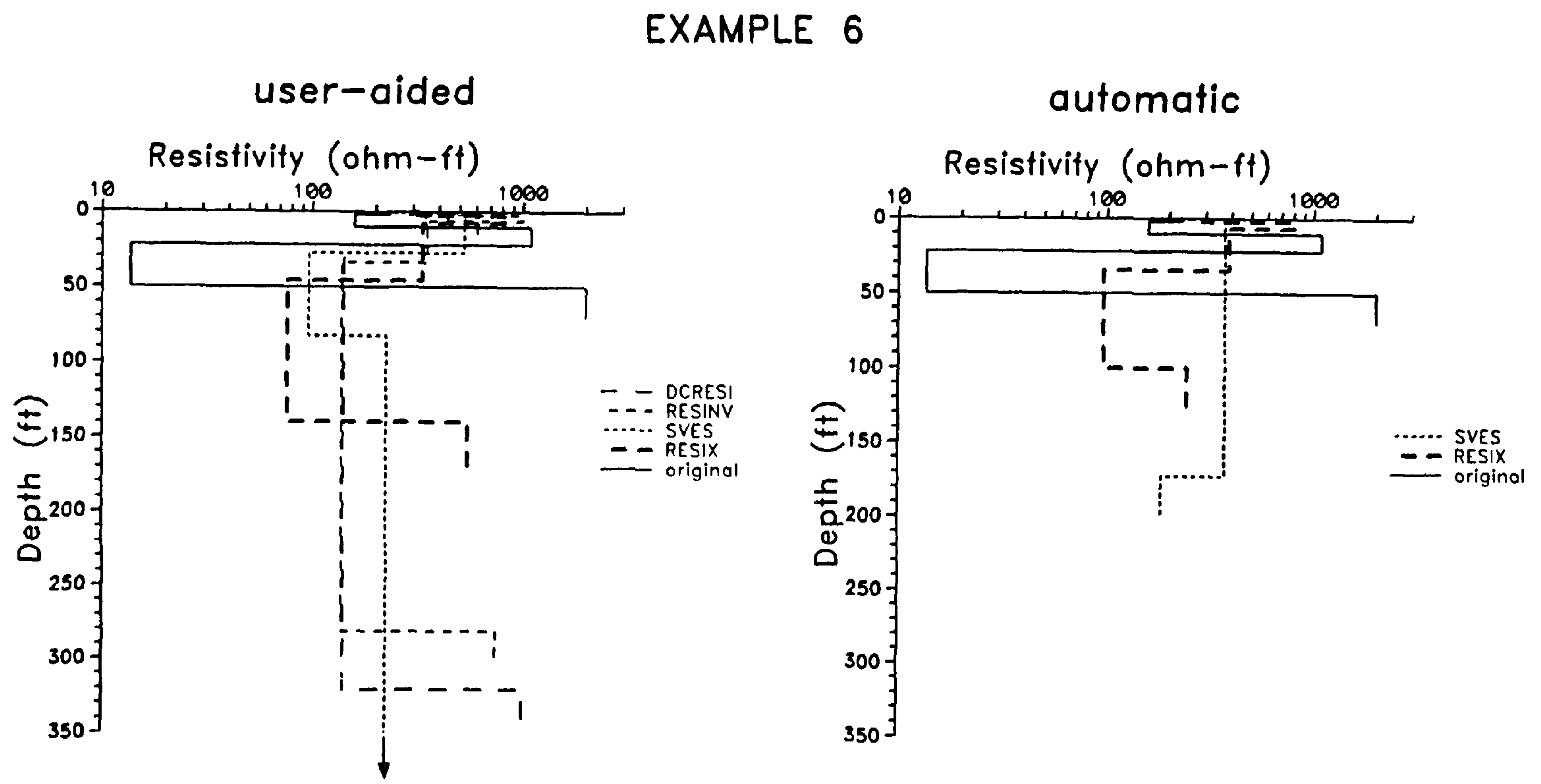


Figure 16. Example 6, Schlumberger field data collected at a landfill site.



(a) (b)

Figure 17. Example 6, inversion results using the (a) user-aided and (b) automatic interpretation methods.

EXAMPLE 7

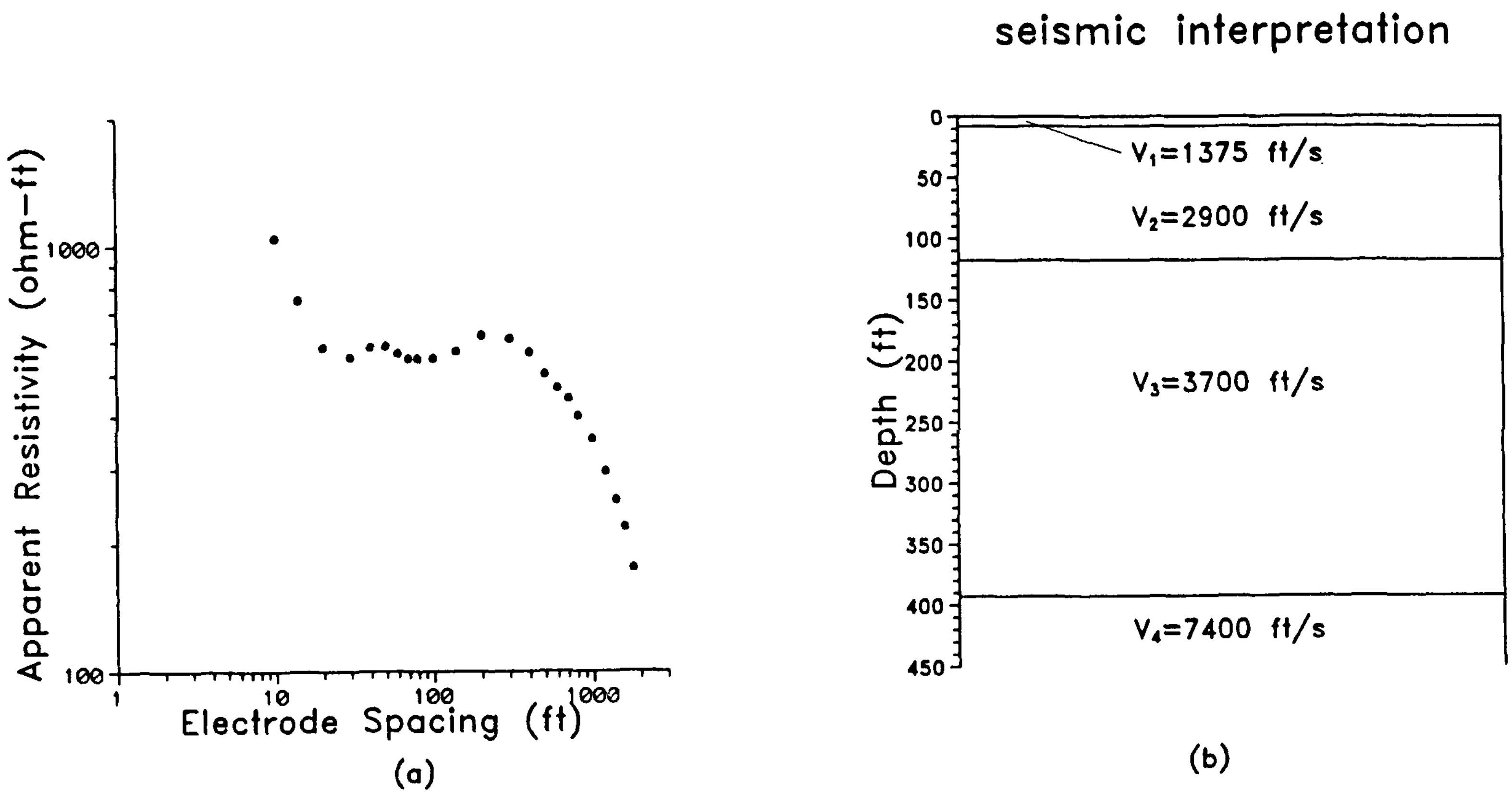


Figure 18. Example 7, (a) Schlumberger resistivity data set SW-19 and (b) seismic interpretation. Data collected at White Sands Missile Range in New Mexico (Butler and Llopis 1984).

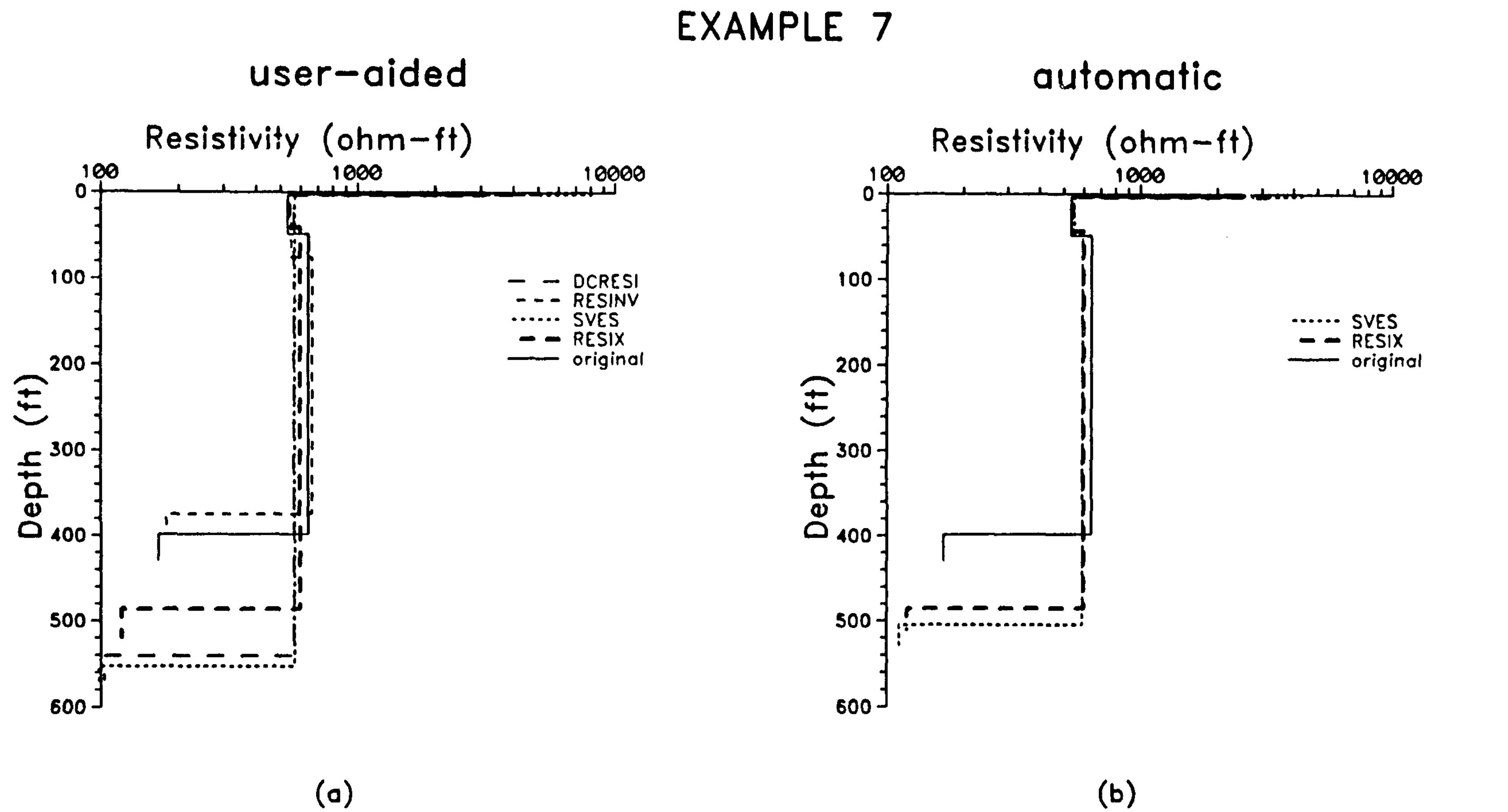


Figure 19. Example 7, inversion results of resistivity data set SW-19 using the (a) user-aided and (b) automatic interpretation methods.

using the automatic RESIX program, the initial model estimate met smoothing criteria (ii), however, the fitting error of the three-layer model exceeded the 10% limit (criteria (iii)), thus the three-layer model was rejected. All inversion results are similar, although the DCRESI first layer resistivity is lower than the other models and the user-aided SVES is a rough approximation of the four-layer models. The resistivity models identify the overburden and two intermediate interfaces, as does the seismic interpretation. The first intermediate interface determined from the resistivity inversion is approximately 80 feet shallower than that determined from the seismic data, and the lower resistivity interface is about 85 feet deeper than the seismic interface. The two methods measure different properties so it is not surprising that the interface depths do not coincide. The four-layer models (RESINV, automatic SVES and RESIX) are comparable to the original interpretation (Butler and Llopis 1984).

43. Resistivity data set T-14 indicates four or five layers while the seismic data identifies three layers (Figure 20). The user-aided and automatic inversion results are given in Figure 21a and 21b, respectively. Programs DCRESI and SVES (user-aided and automatic) found a four-layer model to best fit the data whereas a five-layer model was optimum using the other programs (RESINV and both RESIX). The original interpretation consists of five layers. The second interface in the five-layer resistivity models correlates well with the first seismic interface at a depth of approximately 15 feet. The two methods detect the effects of the water table at much different depths; seismic 96 ft, resistivity 40-50 ft. Again, this is due to the different subsurface properties each technique measures. The deepest interface the resistivity models identify is due to a change in ground-water salinity (Butler and Llopis 1984). Since there is not a significant density contrast, the seismic method is unable to detect this interface.

Examples 9, 10, 11

44. The following three data sets were collected in a desert region of Egypt (Butler et al. 1990). The purpose of collecting this data was to identify possible ground-water sources. Seismic data are not available to correlate with the resistivity data but borehole information is available for

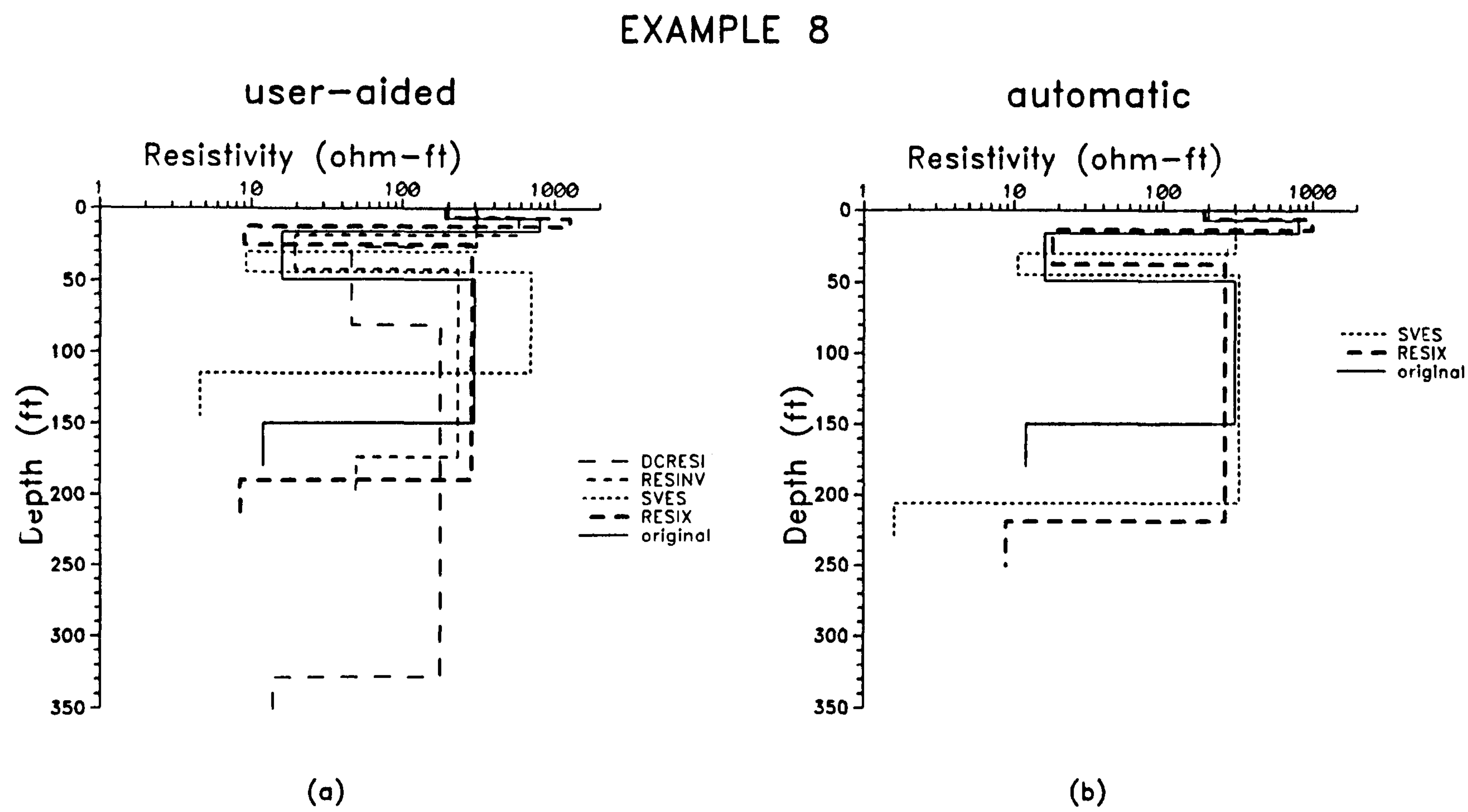


Figure 21. Example 8, inversion results of resistivity data set T-14 using the (a) user-aided and (b) automatic interpretation methods.

correlation with sounding VES-2.

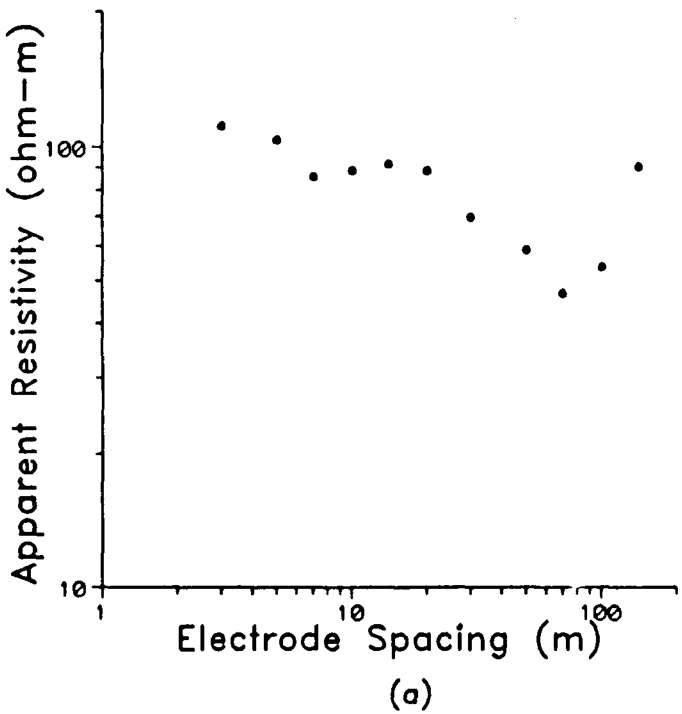
45. A three or four layer structure is suggested by the first data set VES-2. A borehole distinguishes five layers of alternating sand and clay (Figure 22). The user-aided programs DCRESI, RESINV, and RESIX achieve a best fit to the data with a three-layer model, while a four-layer model is best using SVES (Figure 23a). Both automatic modeling programs (SVES and RESIX) fit a four-layer model (Figure 23b). The first and second layer resistivities of the SVES model are nearly the same plus the second layer is very thin, so this model should reduce to three layers. The first two layer resistivities of the RESIX model are also similar and meet smoothing criteria (ii), however, the fitting error of a three-layer model increases more than 10% (criteria (ii)), so the four-layer model is kept.

46. All models have basically a high, low, high resistivity structure. The low resistivity layer corresponds to the zone of saturation. The original interpretation fit five layers to the data (Butler et al. 1990). The six inversion results are a rough approximation to this original interpretation, with the automatic RESIX model fitting quite well.

47. Sounding VES-3 also infers a three or four layer earth (Figure 24). Both the user-aided (Figure 25a) and RESIX automatic programs (Figure 25b) find that a four-layer model adequately fits the data. The SVES automatic inversion fits a three-layer model. The user-aided programs exhibit an alternating high and low resistivity structure as does the original interpretation (Butler et al. 1990), which consists of five layers. However, the third layer is a smoothed representation of the third and fourth layers in the original interpretation, and is much thinner. The automatic inversion models (RESIX and SVES) do not fit the original interpretation as well, having a low-high resistivity sequence.

48. A subsurface structure consisting of three layers is indicated by the sounding curve VES-4 (Figure 26). All user-aided inversion programs were used to fit a three-layer model. The automatic SVES program also fit three layers but RESIX fit a four-layer model (Figure 27). The layer resistivities of all models are similar to the original four-layer interpretation (Butler et al. 1990), but the total layer thickness is about 35 feet greater.

EXAMPLE 9



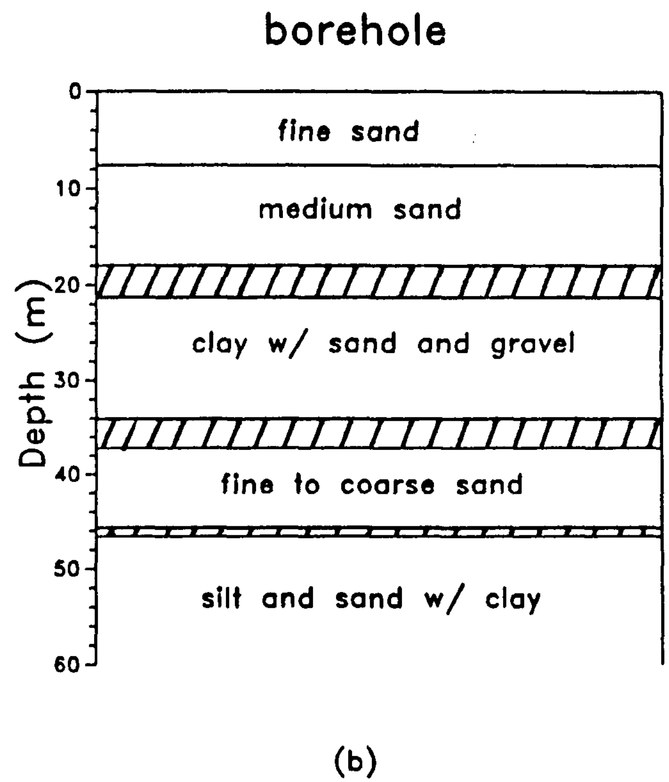


Figure 22. Example 9, (a) Schlumberger sounding curve VES-2 and (b) borehole data. Data collected in a desert region of Egypt (Butler et al. 1990). Hatchured zones represent depth uncertainty on material type change.

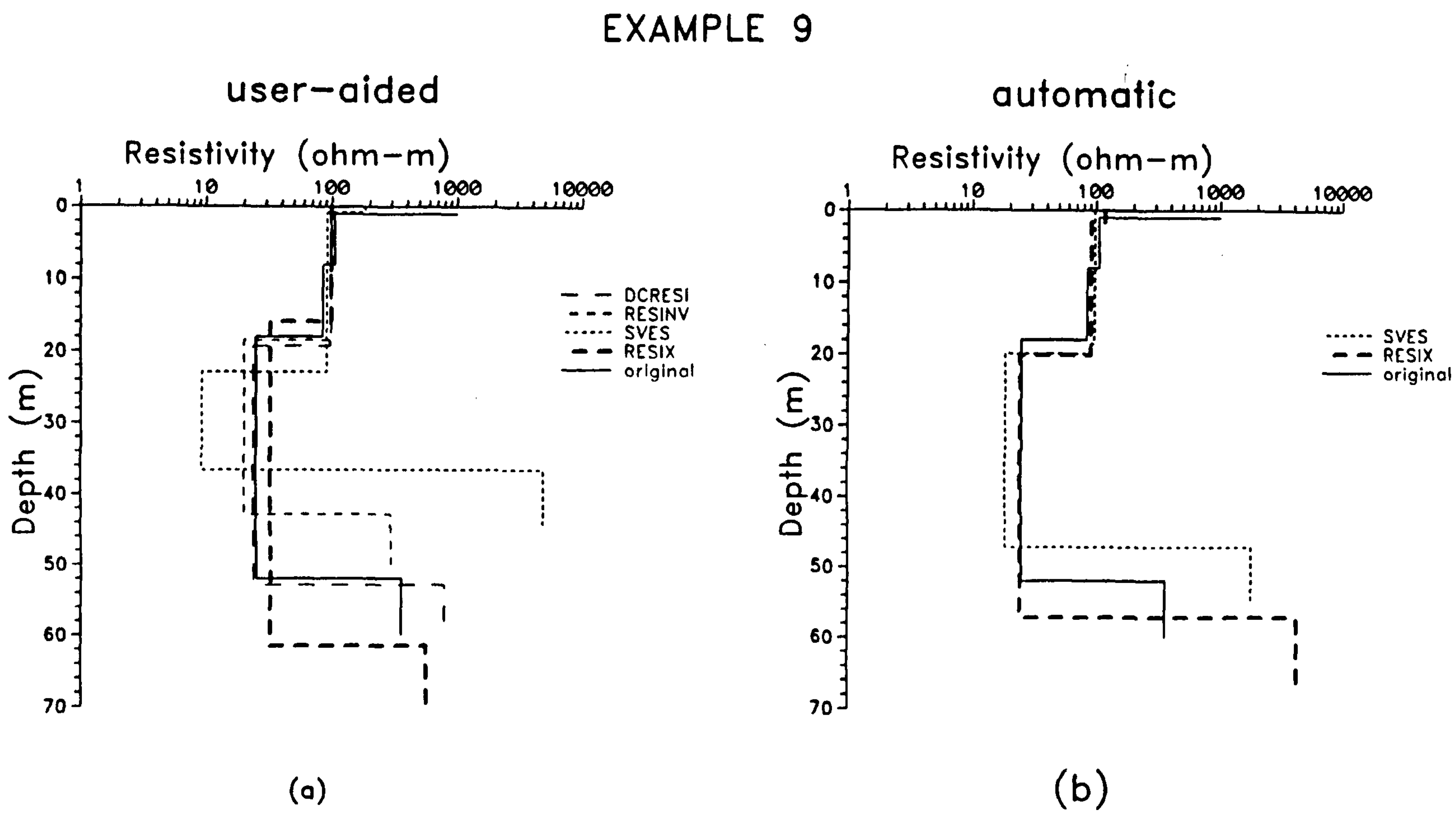


Figure 23. Example 9, inversion results of resistivity data set VES-2 using the (a) user-aided and (b) automatic interpretation methods.

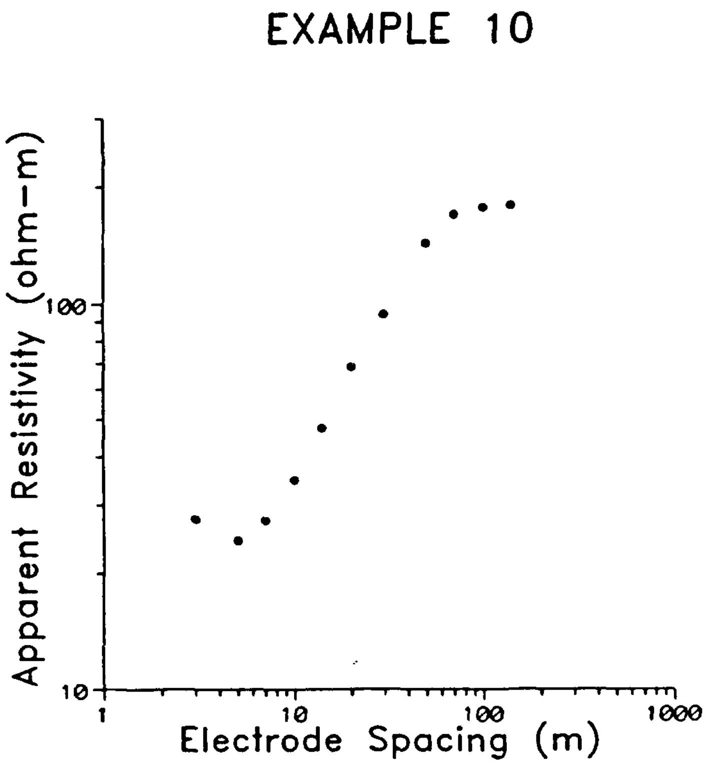


Figure 24. Example 10, Schlumberger sounding curve VES-3. Data collected in a desert region of Egypt (Butler et al. 1990).

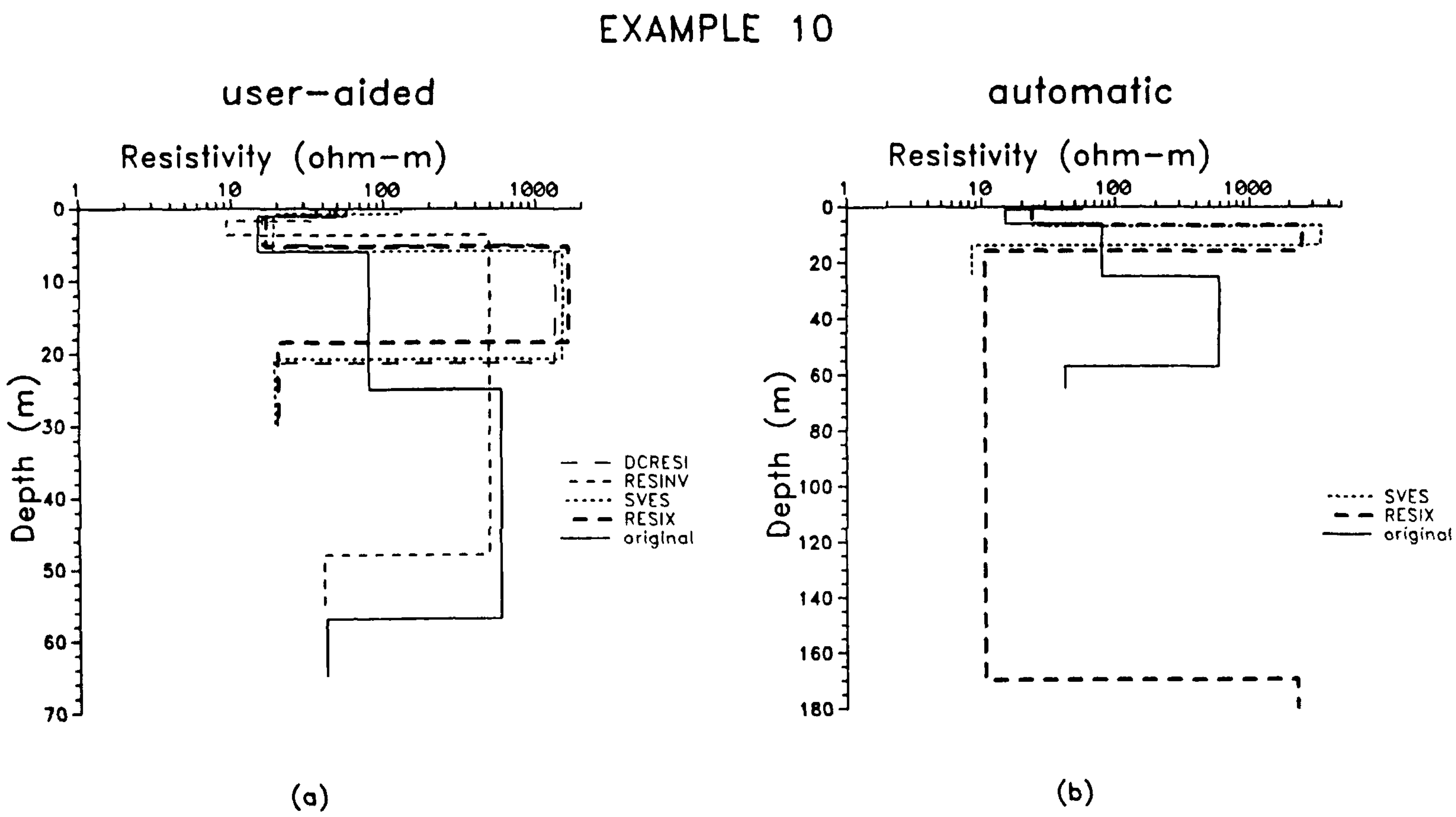


Figure 25. Example 10, inversion results of resistivity data set VES-3 using the (a) user-aided and (b) automatic interpretation methods.

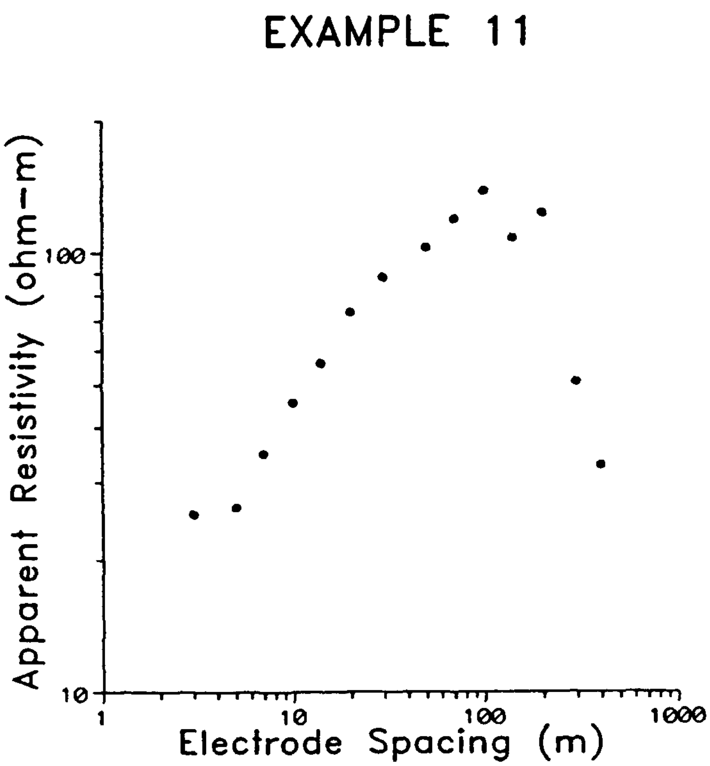


Figure 26. Example 11, Schlumberger sounding curve VES-4. Data collected in a desert region of Egypt (Butler et al. 1990).

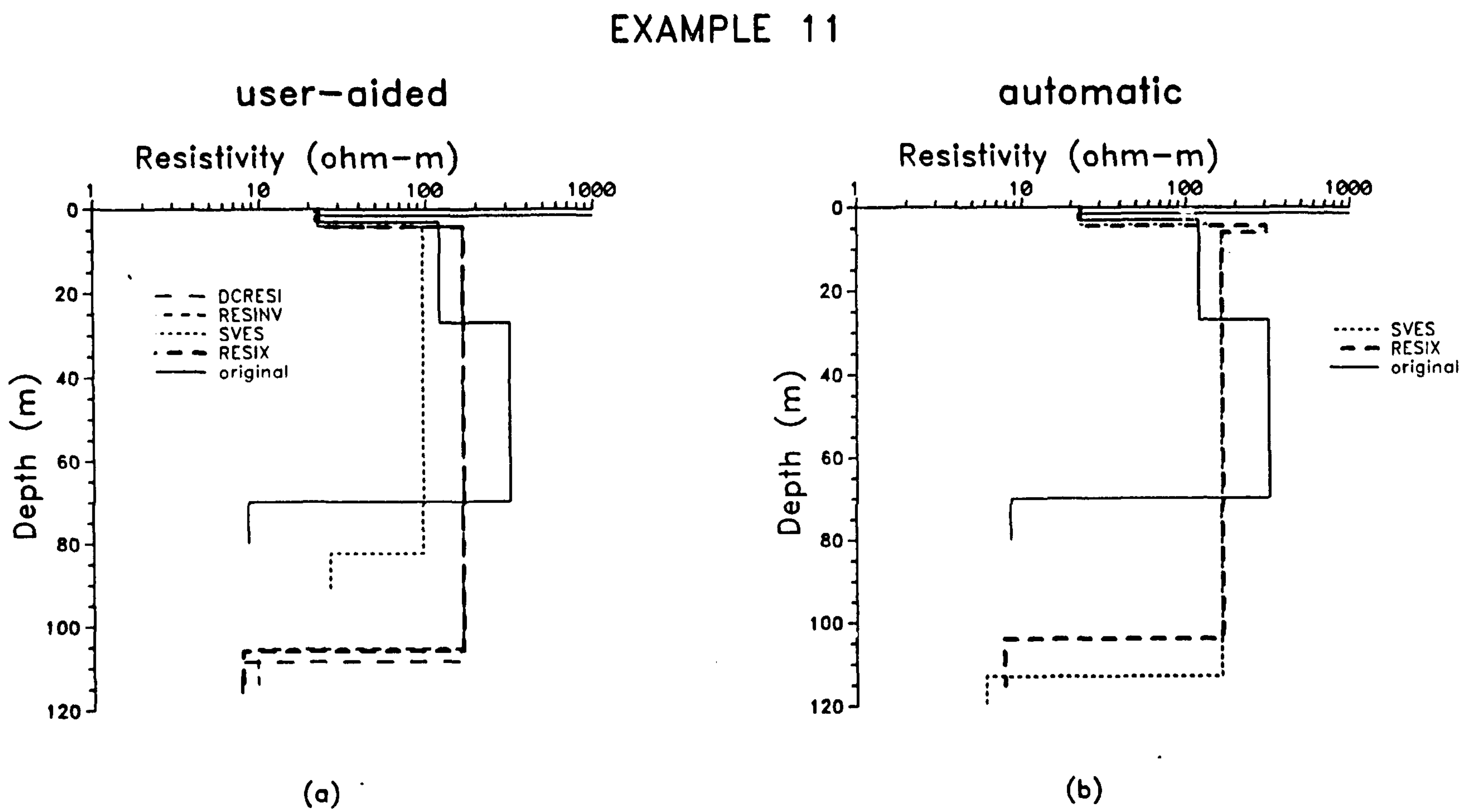


Figure 27. Example 11, inversion results of resistivity data set VES-4 using the (a) user-aided and (b) automatic interpretation methods.

PART VI: SUMMARY AND CONCLUSIONS

49. It is evident from the examples presented that there are differences in the various algorithms available for interpreting d.c. resistivity data. Overall, both the user-aided and automatic interpretation schemes were able to find a model that had some similarity to the true or originally interpreted solution. Table 2 summarizes which inversion algorithm was best at modeling the various data sets. Of the user-aided inversion programs, DCRESI and RESINV performed equally well, with RESIX close behind. RESIX out performed SVES when using the automatic interpretation option. DCRESI is no longer commercially available and does not contain the required automatic interpretation or equivalence analysis routines. The program RESINV also does not contain these routines and it is not in a menu driven format. It would be possible for the WES personnel to revise RESINV to meet our needs, but this would require many man-hours. The only inversion program that performed well and contains the majority of the desired attributes is RESIX PLUS (refer to Table 1). At the present time RESIX does not have direct data input capabilities. However, this in not a major obstacle and two solutions are possible. The company which wrote RESIX, INTERPEX Ltd., is considering writing an interface to allow direct data input, or it is possible that WES personnel could perform this task. Based on the performance of the various inversion algorithms evaluated and the number of desirable attributes each program contains, it is recommended that the program RESIX PLUS (INTERPEX, Ltd., Golden, Colorado) be used as the resistivity interpretation program in the Water Supply Program.

Table 2

Summary of Best Resistivity Interpretation

Program For Modeling Each Data Set

EXAMPLE	USER-AIDED	AUTOMATIC
1	all	RESIX
2	DCRESI	RESIX
3	DCRESI/RESIX	RESIX/SVES
4	none	RESIX
5	RESIX	RESIX
6	none	RESIX
7	RESINV	RESIX/SVES
8	RESINV/RESIX	RESIX
9	DCRESI	RESIX
10	RESINV	none
11	SVES	SVES/RESIX

References

Butler, Dwain K., Gangi, Anthony F., Wahl, Ronald E., Yule, Donald E., and Barnes, Donald E. 1982. "Analytical and Data Processing Techniques for Interpretation of Geophysical Survey Data with Special Application to Cavity Detection." Miscellaneous Paper GL-82-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Butler, Dwain K. and Llopis, José L. 1984. "Assessment of Two Currently Fieldable Geophysical Methods for Military Ground Water Detection," Military Hydrology, Report 6. Miscellaneous Paper EL-79-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Butler, Dwain K., Llopis, José L., Yule, Donald E., Sharp, Michael K., and Dardeau, Elba A. Jr. 1990. "Water Detection Response Team Geophysics Element Case Histories." Technical Report GL-90-23, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Davis, P.A. 1979a. "Development and application of resistivity sounding inversion for several field arrays." M.S. thesis, University of Minnesota, Minneapolis, Minnesota.

__________ 1979b. "Interpretation of resistivity sounding data-Computer programs for solutions to the forward and inverse problems." Information Circular 17, Minnesota Geological Survey, St. Paul, Minnesota.

Department of the Army 1979. Geophysical Exploration. Engineer Manual EM 1110-1-1802, Office of the Chief of Engineers, Washington D.C.

Falls, T.C., Butler, C.D., Webb, B.T., Gates, B.Q., Williamson, J.L., Turnage, G.W., and Chase, A. 1991. "ALBE Geographic information system/user interface/graphics, Volume 1 programmer's guide (version 1.0)." Miscellaneous Paper GL-91-, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Inman, J.R. 1975. "Resistivity inversion with ridge regression." Geophysics, Vol 30, pp 798-817.

Koefoed, O. 1976. "Progress in the direct interpretation of resistivity sounding: an algorithm." Geophys. Prospect., Vol 24, pp 233-240.

Marquardt, D.W. 1963. "An algorithm for least-squares estimation of nonlinear parameters." J. Soc. of Industrial and Applied Mathematics, Vol 11, pp 431-441.

Mooney, H.M. 1979. "Handbook of engineering geophysics, volume 2--Electrical resistivity." Bison Instruments, Inc., Minneapolis, Minnesota.

Orellana, Ernesto and Mooney, H.M. 1966. "Master tables and curves for vertical electrical sounding over layered structures." Madrid Interciecia.

Yule, Donald E. and Sharp, Michael K. 1990. "Seismic refraction data processing software: SEISMO version 2.7." Instruction Report GL-90-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Zohdy, Adel A.R., and Bisdorf, Robert J. 1989. "Programs for the Automatic Processing and Interpretation of Schlumberger Sounding Curves in Quickbasic 4.0." U.S.G.S. Open-File Report 89-137 A.

APPENDIX A: MILITARY REQUIREMENTS FOR GEOPHYSICAL GROUND WATER DETECTION AND EXPLORATION*

*Reprinted from Proceedings, Symposium on Surface and Borehole Geophysical Methods in Ground Water Investigations, Fort Worth, TX, 1985 (Feb.) National Water Well Association, pp 228-248.

MILITARY REQUIREMENTS FOR GEOPHYSICAL GROUND WATER DETECTION AND EXPLORATION

Dwain K. Butler

U. S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

Abstract

Adequate water supply is a critical requirement for support of military operations in arid and semi-arid regions and for fixed military bases. Ground water exploration typically will utilize all available information to aid the interpretation of geophysical survey data and produce an integrated assessment for an area. Situations are envisioned, however, in which little or no supplementary information will be available to aid or constrain the interpretation of geophysical survey data. For this latter case, information about ground water table depth, aquifer thickness, and water quality is required expeditiously at selected, perhaps widely separated, locations. Ground water detection is a terminology properly applied to rapid ground water assessments at selected, widely-spaced locations. Case histories are presented illustrating both ground water exploration and detection. A ground water detection study at five locations on White Sands Missile Range, New Mexico, illustrates the application of seismic refraction, electrical resistivity, loop-loop low induction number electromagnetic (EM), and transient EM methods. Results of the geophysical methods are compared to known geohydrological conditions.

Background

Ground water detection methodology is the subject of several research projects at the U. S. Army Engineer Waterways Experiment Station (WES). The methodology comes under the field of military hydrology, which is a specialized field of study dealing with the effects of surface and subsurface water on the planning and conduct of military operations. Responsibility for management of a Military Hydrology Research Program was assigned to WES by the Office, Chief of Engineers. Ground water detection is part of the water supply thrust area; other thrust areas are weather-hydrology interactions, state of the ground, and streamflow.

There is no device or black box that can be set on the ground at a given location and, with just the press of a button, determine with a 95-percent probability that potable ground water is present at a depth of X feet. Even in the foreseeable future, there is little likelihood that such a device will be available either in this country or elsewhere. In the majority of cases, ground water is usually detected as a matter of course in field investigations not specifically intended for ground water exploration. A Ground Water Detection Workshop was held at WES in January 1982. It was attended by Department of Defense representatives interested in improving military capability to develop and exploit local water sources to support military operations in arid regions. The conclusions of the Geophysics Working Group at the Ground Water Detection Workshop were: (a) there are two currently "fieldable" geophysical methods, electrical resistivity and seismic refraction, that are applicable to the ground water detection problem and may offer a near-term solution to the need for ground water detection capability, and (b) there are several state-of-the-art and emerging geophysical techniques that may have potential in the far-term for application to the ground water detection problem. The near-term solution, i.e., the use of currently fieldable methods, has the potential of significantly reducing the risk of dry holes during water well drilling operations, but the field operations are somewhat cumbersome and time-consuming for possible deployment in support of forward area operations. Development of one or more of the emerging geophysical techniques offers the possibility of delivering something closer to the desired capability than the near-term methodology.

Geohydrological Models

Geophysical exploration for ground water refers to surface remote sensing techniques as shown in Figure 1. The objective of the geophysical surveys in ground water exploration is the determination of subsurface structural or stratigraphic indicators of the presence of ground water

I. Direct Methods

  A. Drilling
  B. Surface Reconnaissance

II. Indirect

  A. Aerial/Satellite Remote Sensing Methods
     Objectives: Structural, Geomorphic, and Vegetative Surface Indicators of Ground Water Occurrence.
  B. Surface Remote Sensing (Geophysical) Methods
     Objectives: Structural, Stratigraphic, and Aquifer Property Subsurface Indicators of Ground Water Occurrence.

Figure 1. Methods for ground water exploration

or the measurement of a parameter that is an actual physical property of the aquifer itself. The indicators are indirect clues to the presence of ground water. A physical property of the aquifer itself could be a more direct clue of the presence of ground water. It is important to be aware of the various ways in which usable quantities of ground water may occur in the subsurface. Ground water occurrence can be illustrated by models which illustrate unconfined aquifers (Figures 2 and 3), confined aquifers (Figure 2), perched water (Figure 3), and water which is concentrated along fracture zones in otherwise nearly impervious rock (Figure 4). As suggested by Figures 2, 3, and 5, more than one of the above models or conditions will more than likely occur at a given site.

Detection Versus Exploration

Geophysical methods are routinely used throughout the world in exploration programs for the assessment and development of ground water resources. The geophysical methods that are predominantly used in these ground water exploration programs are gravity, electrical resistivity, and seismic refraction methods. Although occasionally only one of these methods will be used in an exploration program, generally at least two of the methods are used in a complementary approach. A geophysical ground water exploration program will normally use all available borehole and other geological data in order to produce the best possible assessment of the ground water potential and conditions in an area.

The primary objective of geophysical ground water exploration is the mapping of subsurface structural and stratigraphic indicators of the possible occurrence of ground water, such as buried river channels, fracture zones in bedrock, confining layers (aquacludes), etc. Actual detection of the ground water table with any of the geophysical surveys may be noted but may not be of primary importance in the overall ground water exploration assessment. Figure 6 is an example of the use of the seismic refraction method to delineate a buried channel in an arid region in western Kansas; identification of material type was made by correlation with exploratory borings near each end of the profile. In this example, the water table was actually detected by the occurrence of the characteristic seismic velocity (to be discussed later in this paper) in the central part of the survey profile. However, even if the ground water table had not been detected in this example, the stratigraphic indicators would dictate the greatest ground water potential for a well placed in the center of the subsurface channel.

The expression "ground water detection," in contrast to ground water exploration, applies to the concept of actually detecting the presence (or absence) of ground water and the depth to the water table beneath a given "point" on the surface by conducting one or more types of geophysical tests at that point. In the ideal case, the aquifer thickness and water quality would also be determined. For some cases, information regarding ground water occurrence and other geological factors might be available but, in general, the assessment of the presence of ground water must rely solely on the geophysical results at the given surface location in the detection scenario. It is envisioned, however, that many times the geophysical ground water surveys would be conducted

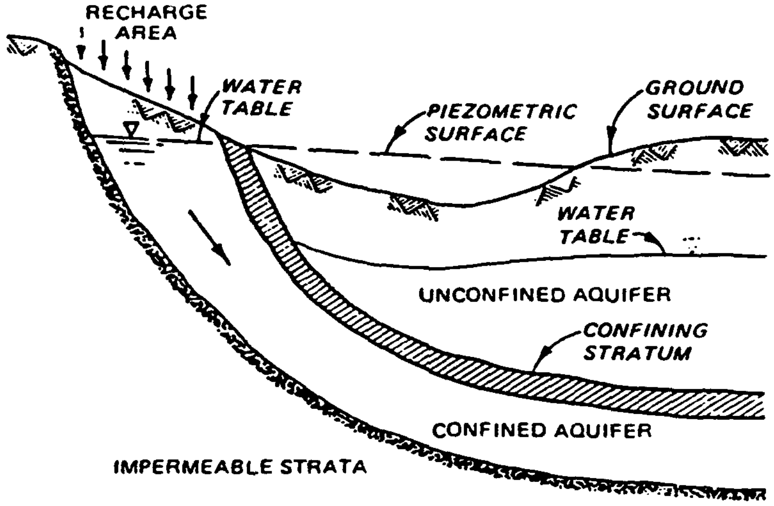


Figure 2. Hydrogeological model of confined and unconfined aquifers

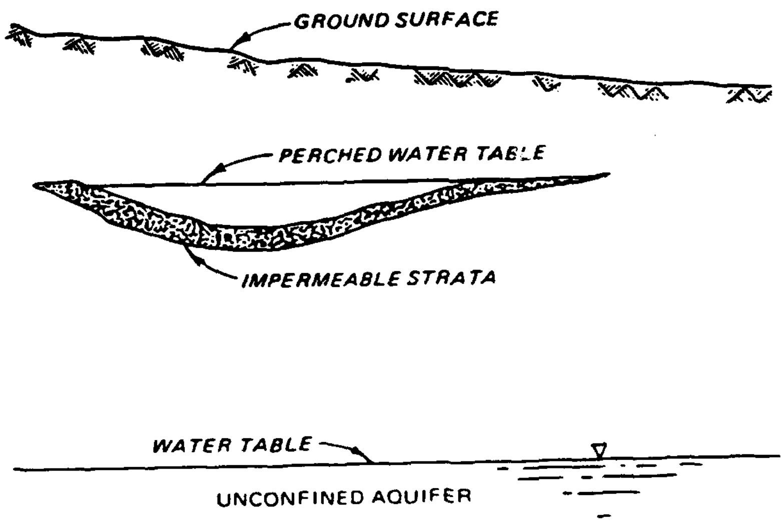


Figure 3. Hydrogeological model of perched water table

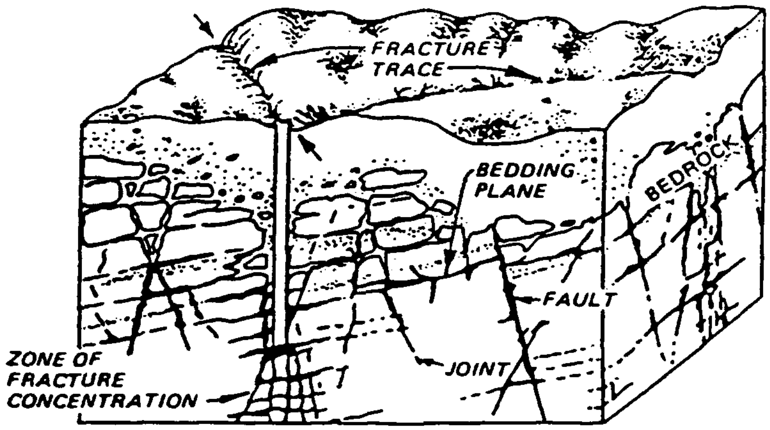


Figure 4. Hydrogeological model of ground water concentrated on fracture zones

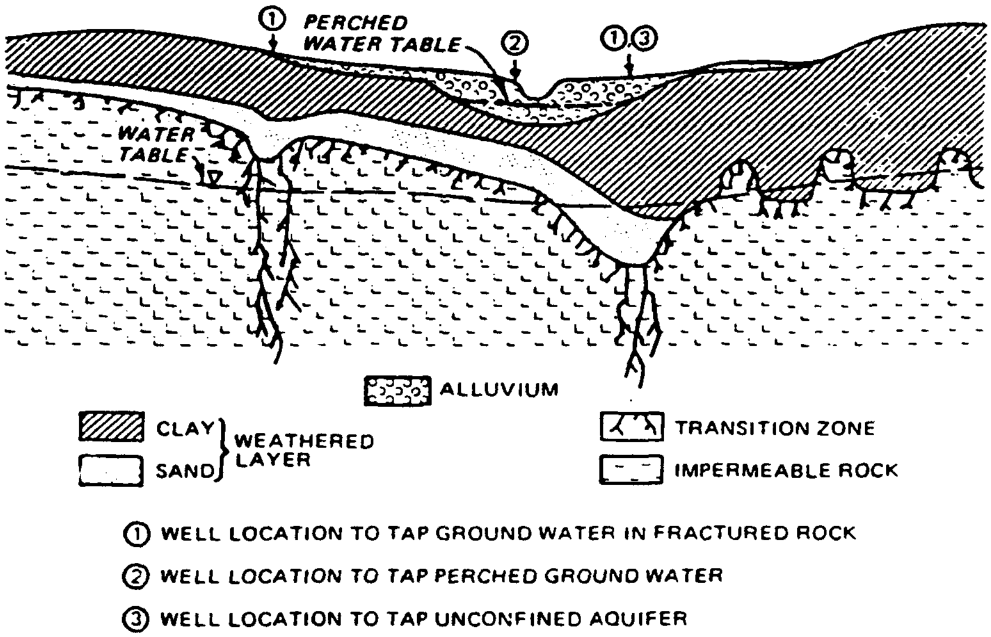


Figure 5. Hydrogeological model illustrating multiple modes of ground water occurrence

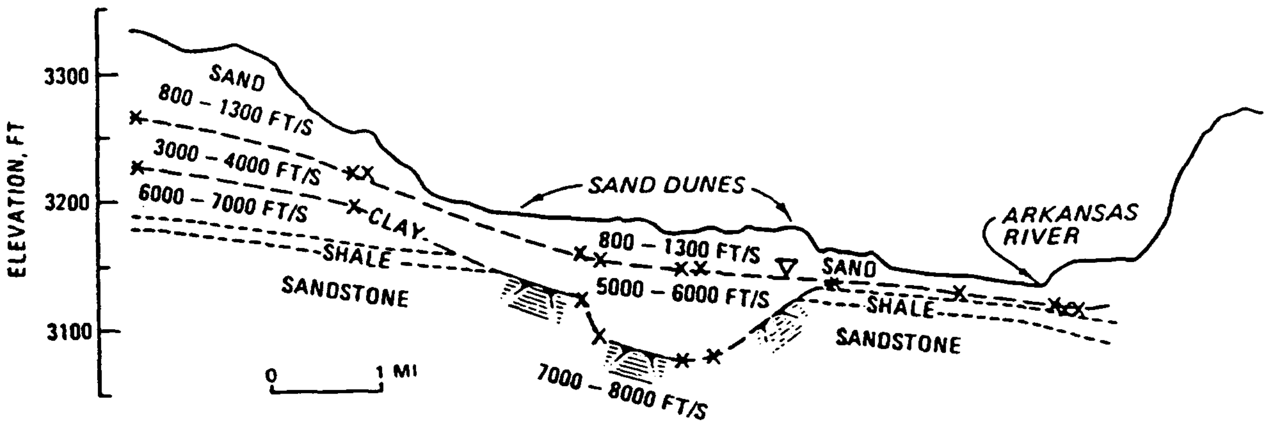


Figure 6. Example of water table detection and of delineation of a buried channel in western Kansas by the seismic refraction method

to aid in choosing between alternate sites in an area already identified as having good ground water potential by other methods. Of the three geophysical methods most commonly used in ground water exploration programs, only two, electrical resistivity and seismic refraction, are applicable to the ground water detection problem. Figure 7 summarizes geophysical methods and their present or projected applicability to ground water exploration and/or detection programs. Detection principles for the electrical resistivity and seismic refraction methods are discussed below.

Detection Principles

Electrical resistivity method

The electrical resistivity method applicable to the ground water detection problem is vertical resistivity sounding, where the objective is to make electrical measurements at the surface from which the vertical variation of electrical resistivity with depth can be interpreted. The resistivity of a material is a fundamental geophysical property of the material. Although the range of resistivities of geological materials is that of the order of 10^{20} ohm-m, the range commonly encountered in ground water exploration and detection is typically 10^5 ohm-m.

Most soils and rocks conduct current primarily electrolytically, i.e., through interstitial pore fluid. Thus, porosity, water content, and dissolved electrolytes in the water are the controlling factors in determining resistivity rather than the soil or rock type. A major exception to this generalization are clays, which can conduct current both electrolytically and electronically. The general relation between bulk resistivity ρ_b of a soil or rock and the porosity ϕ (volume fraction), pore fluid saturation S_w (volume fraction of ϕ), and pore fluid resistivity ρ_w can be expressed by the following empirical equation:

$$\rho_b = a\rho_w \phi^{-m} S_w^{-n} ,$$

Geophysical Method	Ground Water Detection	Ground Water Exploration/Assessment
Seismic Refraction	X	X
Seismic Reflection (Profiling)		X
Seismic Reflection (V_p/V_s Sounding)	X	
Electrical Resistivity	X	X
Gravity		X
CW Electromagnetic (EM)	?	X
Transient EM	X	X
Pulse "Radar" EM	?	?
Magnetic		X
Airborne (Gravity, Magnetic, EM)		X

Figure 7. Summary of applicability of geophysical methods to ground water exploration and detection

where a , m , and n are constants which depend on the soil or rock type. Below the water table $S_w = 1$ (100 percent saturation). Qualitatively, equation 1 indicates: (a) as porosity increases, bulk resistivity decreases; (b) as pore fluid saturation increases, bulk resistivity decreases; and (c) as pore fluid resistivity increases, bulk resistivity increases.

A common and successful use of resistivity sounding is for detecting the fresh water/salt water interface, which will always be indicated by the occurrence of a prominent resistivity decrease. Detection of the water table itself is a more difficult problem. Under favorable conditions, the water table will be detected as the top of a conductive or less resistive layer; since, except for unusual conditions, even fresh potable ground water is much lower in resistivity than the dry aquifer material. The most favorable conditions will be when the water table occurs in unconsolidated sediments with little clay content. Dry silts, sands, and gravels will have resistivities of 300 ohm-m and greater; for fresh water, the resistivity at the water table will typically decrease to a range of 20 to 100 ohm-m in areas like the southwestern United States. In sediments with considerable clay content, the resistivity contrast will be much smaller and may be undetectable. At the fresh water/salt water interface, the resistivity of the aquifer will decrease considerably, perhaps to $<$ 1 ohm-m. Zohdy et al. (1969, 1974) adopted a qualitative criterion of $\rho_b \sim 10$ ohm-m to differentiate fresh from saline ground water conditions in a large ground water assessment program

at White Sands, New Mexico. Clays can have resistivities intermediate to the resistivities of highly saline and fresh aquifer conditions.

Seismic refraction method

The seismic method applicable to the ground water detection problem (in the near-term) is the refraction method. From a seismic refraction survey at a given location, it is possible in principle to determine depths to interfaces between materials with contrasting bulk density and seismic velocity and to determine the seismic velocities of the different materials. Generally, only compression-wave (P-wave) velocities are easily determined from seismic refraction surveys.

The physical principle involved in the detection of the water table by seismic methods is that the P-wave velocity of saturated sediments is considerably greater than the same sediments in dry or only partially saturated conditions. Typically, the P-wave velocity will increase from 300 - 700 m/sec to 1375 - 1675 m/sec at the water table, where the water table occurs at shallow depths ($\lesssim$ 30 m) in unconsolidated sediments (silts, sands, and gravels). The occurrence of a characteristic 1,500 m/sec velocity at shallow depths at a site is generally strongly indicative of a ground water table, although some weathered rocks and massive clay deposits can have this velocity also.

If the water table occurs at greater depths (> 30 m, for example), the seismic velocity of the saturated sediments can be as high as 2,300 m/sec; but in these cases, the velocity of the unsaturated sediments just above the water table can be as high as 1,200 m/sec. The smallest velocity contrast at the water table will occur in very fine-grained sediments, where the velocity contrast can be as small as 150 m/sec. When the water table occurs as an unconfined surface in rock, there will always be a velocity increase at the water table, but it may be small. Where the ground water occurs in a confined rock aquifer, there may be little in the seismic data to suggest the presence of ground water without independent or complementary information. Whether the water table in an unconfined aquifer will be detected or not depends on the thickness of the saturated zone above high-velocity rock. In some cases, where the contrast in seismic velocity between rock and saturated sediments is large and the saturated zone is thin relative to its depth, the water table refraction will not be detected in an "ordinary" seismic refraction interpretation (blind zone problem).

Complementary methods

The resistivity and refraction methods are complementary in the sense that they respond to or detect different physical properties of geologic materials. Both methods can detect the water table, hence, the presence of ground water under certain conditions. In cases where both methods detect the water table, one method serves to confirm the results of the other method or to resolve ambiguities. Certain conditions, however, such as the presence of a fresh water/salt water interface, can be detected by one method but not the other.

When depths to interfaces determined by geophysical methods are compared to "ground truth data" from nearby boreholes, typically the agreement is within ±10% for the seismic refraction method and ±20% for the electrical resistivity method. Of course, the difference between the actual interface depth and geophysical interface depth can occasionally be greater due to the effects of blind zones and velocity inversions (departures from the normally assumed case where seismic velocity increases with depth) in seismic refraction interpretation and highly equivalent solutions in electrical resistivity interpretation. The problem of geophysical determination of the water table depth is complicated by the physical nature of the "interface." The "geophysical interface" commonly may be somewhere within the capillary zone, the velocity and resistivity interfaces may be different, and neither may agree with the standing water depth in a borehole (and the standing water depth itself may be different from the actual water table). The difference in geophysical and borehole water table depth determinations will be greatest in fine-grained sediments and least in coarse-grained sediments.

Emerging Technology

An advancing technology is the use of seismic reflection methods to determine both compression (V_p) and shear-wave (V_s) velocities from primary reflection records (collections of all geophones receiving signals from a single source location). Thus, both compression- and shear-wave interval velocities can conceivably be determined from a single "split-dip" spread setup, although different sources might be required to generate separate compression- and shear-wave reflection records. In this procedure, V_p/V_s ratios would be determined as a function of depth and, due to the fact that shear-wave velocities are generally much less affected by water saturation than compression-wave velocities, the V_p/V_s profile should be highly indicative of the occurrences of ground water. Because only a single reflection spread setup is required, the logistical complexities associated with the continuous reflection profiling procedure are avoided.

Electromagnetic (EM) methods

If there is ever a device that even comes close to the "black box" water detector ideal, it will likely be an EM device. There are numerous EM techniques ranging from near-DC induction techniques to GHz wave propagation techniques. Hopefully, some innate property of the aquifer system will ultimately be amenable to interrogation or probing by an EM technique and allow direct ground water detection. Direct ground water detection, however, must be viewed as a long-term goal, and the immediate application of the EM methods is as a replacement or supplement to electrical resistivity in a complementary exploration or detection program.

There are several EM techniques such as magnetotellurics and various types of low frequency, continuous wave induction (CWEM) methods that can be used to determine resistivity or conductivity as a function of depth. Compared to the electrical resistivity techniques discussed

previously, these EM techniques can be more rapid and less logistically cumbersome, and they do not require surface contact.

One of the most promising of the emerging technologies is the transient electromagnetic (TEM) method. In the TEM method, a very broad bandwidth EM signal is input to the ground and, because the signal is transient (i.e., not a continuous wave source), very high power levels are possible and measurements can be made during the off-time of the transmitter. The return signal is interpreted to give resistivity as a function of depth. The exciting aspect of the TEM method is that as many as 20 soundings per day can be conducted under favorable conditions. The TEM method still has the same non-uniqueness as any other method used to determine resistivity as a function of depth; however, the TEM method has superior vertical and lateral resolution and is less effected by lateral variations than electrical resistivity and other EM methods.

Ground Water Detection Field Trials

Two field sites were selected as representative of two common aquifers: an unconfined alluvial aquifer and a confined (artesian) rock aquifer. White Sands Missile Range, New Mexico, was selected as the alluvial aquifer site, and Fort Carson, Colorado, as the confined rock aquifer site. Geophysical investigations at the field sites were conducted in two phases. In the first phase, electrical resistivity and seismic refraction surveys were conducted at five widely separated locations at White Sands and at one location at Fort Carson. During the second phase, CWEM surveys were conducted at the five locations at White Sands and at Fort Carson, and TEM surveys were conducted at four of the White Sands locations. This paper will specifically address selected results from the White Sands locations where all four geophysical techniques were applied. Complete details about the field test sites and the results of the first phase of field investigations are given by Butler and Llopis (1984), and results of the CWEM surveys of the second phase are given by Butler (1984).

Figures 8 and 9 illustrate the results of seismic refraction and electrical resistivity surveys at the SW-19 location at White Sands. The geophysical models resulting from the data in Figures 8 and 9 are shown graphically in Figure 10. A ground water assessment or geohydrological model is deduced from the geophysical models using the detection principles discussed earlier. The interpreted geohydrological model for SW-19 is shown in Figure 10.

Geophysical ground water assessments for all five locations at White Sands are summarized in Table 1. The known geological and ground water information about the five locations are summarized in Table 2. Comparison of Tables 1 and 2 indicates general qualitative agreement between the geophysical ground water assessments and the known ground water data for all the locations except HTA-1. The predicted water table depths are consistently too shallow, however, compared to borehole water depth measurements, by amounts ranging from 12 percent at SW-19 to 28 percent at B-30 and T-14. Direct application of the detection principles resulted in misidentification of the water table in the case

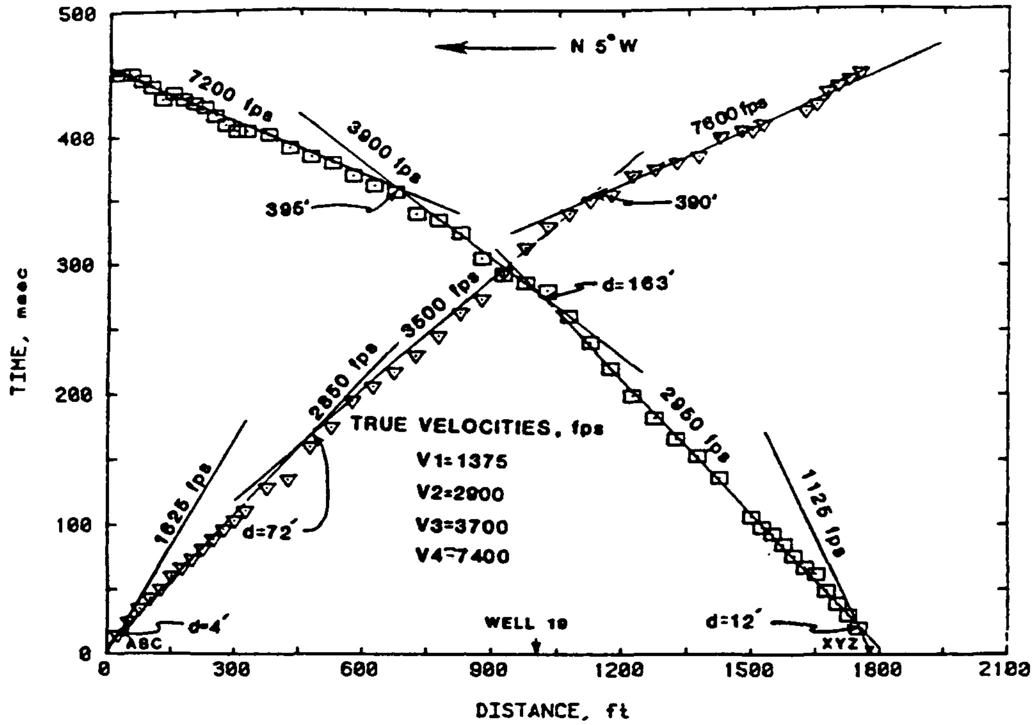


Figure 8. Example of seismic refraction results, SW-19 site, White Sands, New Mexico

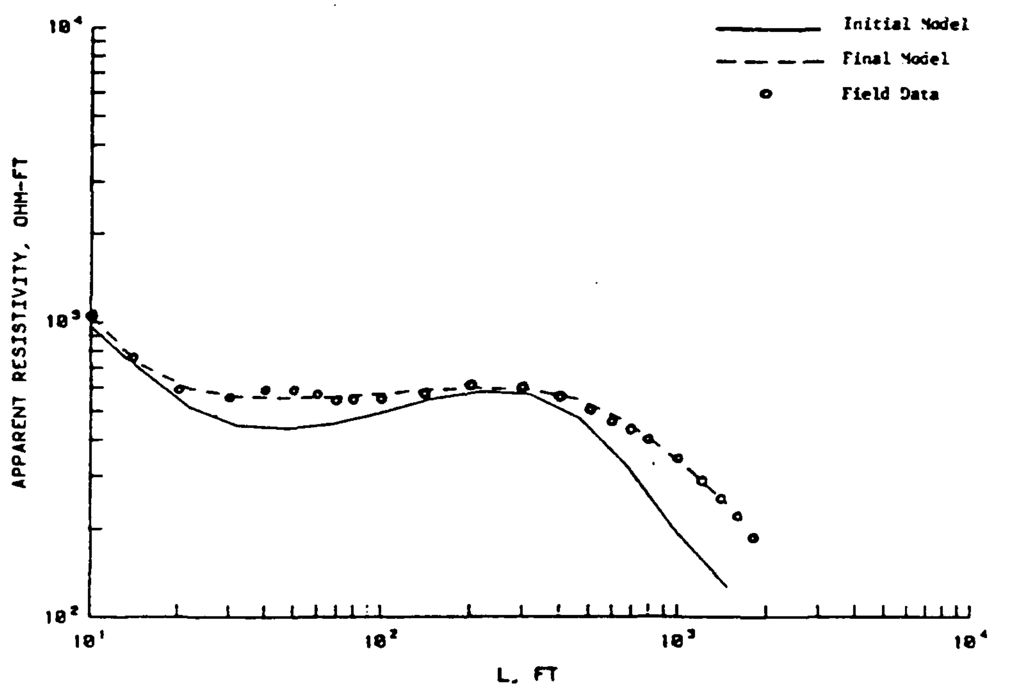


Figure 9. Example of resistivity interpretation procedures for SW-19 site, White Sands, New Mexico

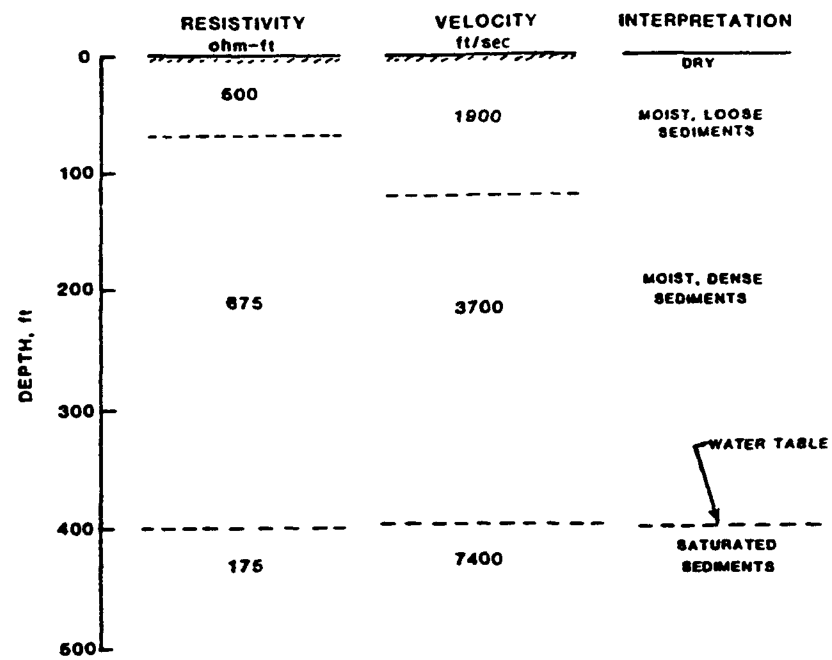


Figure 10. Geophysical models and interpretation for the SW-19 site, White Sands, New Mexico

Table 1

Summary of White Sands Geophysical Ground Water Assessments

Location	Predicted Water Table Depth, Ft	Water Quality Statement	Predicted Aquifer Thickness	Confidence in Ground Water Assessment
HTA-1	8	Fresh	100 ft	Poor
B-30	65	Fresh from 65-125 ft, becoming very saline below 125 ft	?	Fair to Good
T-14	95	Fresh from 95-150 ft, becoming saline below 150 ft	?	Poor to fair
MAR	160	Fresh from 160-300 ft; very saline from 300-1000 ft	Base of aquifer, 1000 ft	Fair
SW-19	400	Fresh	?	Very Good

Table 2

Summary of Geologic/Ground Water Information

For White Sands Test Locations

Location	Measured Water Table		Water Quality* (Resistivity) ohm-ft	Type Geologic Information Available and Summary	Comments
	Depth, ft/ Date	Variation ft			
HTA-1	64 (2/14/83)	6	50 fresh	Limited borehole lithology info. Sand and gravel to 82 ft.. Weathered granite encountered at 82 ft.	Natural gamma and neutron borehole geophysical logs
B-30	89.5 (2/15/83)	1	<4 (@185 ft) saline	None	Natural gamma and neutron borehole geophysical logs
T-14	132 (2/16/83)	1	21 (@200 ft) 22 (@300 ft) marginal	Borehole lithology log for entire 6000-ft depth. Sand with silt and clay, 0-105 ft; clay with sand and silty, 105-220 ft; sand with clay, 120-180 ft; clay with sand and silt, 180-430 ft.	Complete set of borehole geophysical logs from 400-6000 ft

(Continued)

* Generally fresh water is considered to have <1000 mg/ℓ total dissolved solids. This criteria converts approximately to a "specific conductance" <1560 hoscm or a resistivity >21 ohm-ft.

Table 2 (Concluded)

Location	Measured Water Table: Depth, ft/ Date	Measured Water Table: Variation ft	Water Quality* (Resistivity) ohm-ft	Type Geologic Information Available and Summary	Comments
MAR	214 (MAR-2; 2/14/83 220 (MAR-2; 1981)	1	32 (~300 ft 0.6 (@750 ft in MAR-2 and MAR-3) fresh (@300 ft)	Borehole lithology log. Gravel, 0-112 ft; clay, 112-160 ft; gravel, 160-165; clay, 165-200; gravel 220-210; clay, 210-225; etc, predominantly clay below 630 ft.	Electric logs available
SW-19	454 (2/25/83) (427 for SW-18) (514 for SW-20)	5	85 (>400 ft) fresh	Limited material descriptions. Poorly sorted sands and gravels to >900 ft.	Nonpumping water level: 409 ft (7/22/64) (402 ft, SW-18; 462 ft, SW-20)

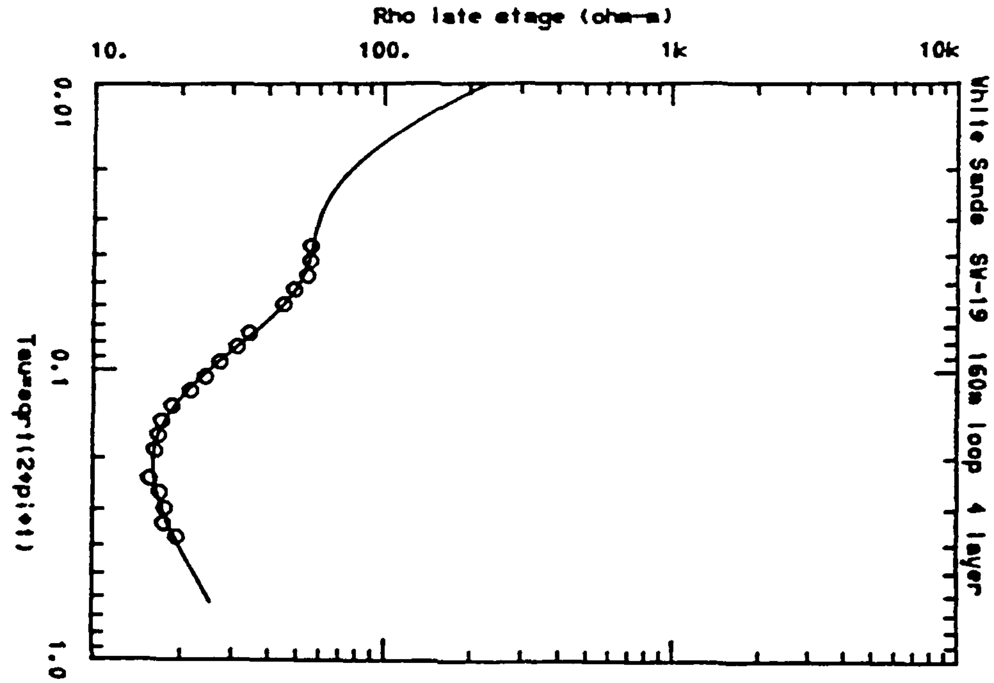


Figure 11. Late stage TEM apparent resistivity data (circles) and a four-layer model fit to the data (solid curve), SW-19 site

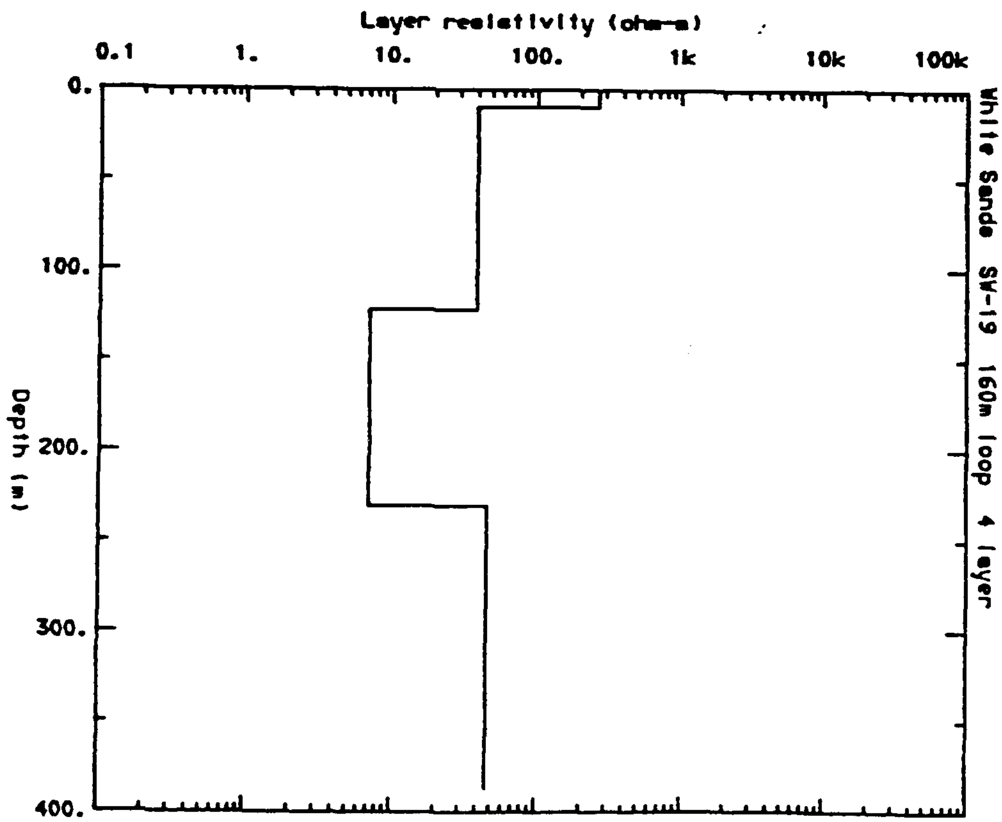


Figure 12. Resistivity model for SW-19 site corresponding to the solid curve in Figure 11

Table 3

Comparison of Measured and Predicted Depths at Three White Sands Locations

	B-30	T-14	SW-19
Measured Water Table Depth (m)	27	40	138††
Predicted Water Table Depth (m)	20**	29**	122
WES Electrical Resistivity Interface* (m)	38(30-46)†	46	122†††
USGS Electrical Resistivity Interface* (m)	46(39-57)†	49	--
TEM Resistivity Interface (m)	30	50-62†	122†††

* Selected White Sands data were also interpreted using a USGS inversion program.

** Based on seismic refraction model.

† Range of model predictions for equivalent solutions.

†† At production well.

††† 150 m from production well.

between the predicted water table and resistivity interface depths. For T-14, the TEM interface agrees with the electrical resistivity interface; while for B-30, the TEM interface depth is within 10 percent of the measured water table depth. The TEM interface for SW-19 agrees exactly with the seismic refraction and electrical resistivity interfaces.

The TEM method fulfilled all expectations regarding ease and rapidity of field use and depth of investigation capability. Although the TEM method is not a stand-alone ground water detection device, it is a possible replacement for electrical resistivity in a complementary geophysical ground water detection methodology. The primary problem with the TEM method currently is the lack of commonly available interpretation tools. There are only limited numbers of master curve solutions available. Also, even the direct TEM multi-layer response problem requires a minicomputer, and the USGS multi-layer inverse program currently operates on a VAX 11/780. Hopefully, inverse programs can be configured to operate on the emerging "super-microcomputers."

Conclusions

Based on the results of this work and other work reported in the literature, the following conclusions are made regarding the applicability of a complementary geophysical methodology for ground water detection:

a. For cases in which the water table occurs in coarse-grained sediments (sands and gravels), the geophysical methods can be used very successfully for ground water detection.

b. For cases in which the water table occurs in fine-grained sediments (clayey sands, silts, silty clays, sandy clays, etc.), the geophysical methods can be used for ground water detection; however, the interpretation will sometimes not be as straightforward as for case *a*, and the difference between predicted and actual water table depth can sometimes be much greater than for case *a*.

c. A fresh water/salt water interface is easily detected by the electrical resistivity method or TEM method, but will not show as an interface in seismic refraction results; detection of this interface is useful in that any fresh water present will be shallower than the interface depth.

d. Rock aquifers can be detected by the geophysical methods, but there may be nothing in the survey results to differentiate a rock aquifer from an unsaturated rock unit (except for the case where the rock unit has high resistivity, in which case the unit is not an aquifer).

e. For some field situations, such as at the Fort Carson site, topographic variations and complex, lateral geologic changes make a straightforward data interpretation impossible.

f. In some cases, such as the HTA-1 location at White Sands, the straightforward interpretation method can lead to false identification of the water table.

g. In order to be conservative when specifying drilling depths, geophysical water table depth estimates should be increased by 30 to 40 percent.

h. It is envisioned that the desired depth of investigation will probably be dictated by considerations such as maximum desired drilling depth or maximum probable depth to water in an area; geophysical ground water assessment productivity is strongly dependent on depth of investigation.

The conclusions of the study can be summarized as follows: Complementary seismic refraction and electrical resistivity surveys (a) can generally be used successfully for ground water detection when the water table occurs in unconsolidated sediments, and (b) can generally not be used successfully for detection of ground water in confined rock aquifers. For the case of rock aquifers, a ground water exploration program is required. The complementary geophysical methodology currently fieldable consists of seismic refraction and electrical resistivity methods. In the near future, the TEM method may advantageously replace the electrical resistivity method.

Military Deployment of Geophysical Ground Water Detection Capability

Development of ground water detection and assessment capability in the military is developing in conjunction with water well drilling and production capability. Geophysical methodology will never be applied in a stand-alone mode but always as part of an integrated system approach. Figure 13 illustrates a possible flow sequence for field deployment.

The key problems which must be addressed are the skill levels required for the geophysical survey teams and the organizational structure. If the decision is made to develop a geophysical ground water detection/exploration capability in or for the field military forces, the following options are considered feasible:

a. Recruit or assign junior officers with degrees in geology, geophysics, or other science/engineering fields with strong geoscience backgrounds to teams which receive intensive specialized training.

b. Utilize teams with special training to conduct surveys and then relay data to a rear area interpretation unit or data analysis contractor that could handle data from several survey units and be better able to incorporate information from ground water maps and data bases into the ground water assessments.

c. Develop geophysical survey expertise in National Guard or Reserve units which already have identified professional geoscience expertise.

c. Establish arrangements with Government agencies and/or geophysical firms for on-call geophysical testing and interpretation services for areas that are reasonably secure; these personnel should have full access to ground water maps and data bases. A quick-reaction team is a possible approach.

It is important that the military track and contribute to research and development on state-of-the-art and emerging geophysical techniques for ground water detection, such as frequency-domain and time-domain electromagnetic methods and the concept of determining the ratio of compression wave to shear wave seismic velocities as a function of depth as a ground water indicator. Another important area is the development of training manuals and programs for geophysical survey operators and for geophysical ground water interpretation procedures. The ultimate goal is the development of an automated system for assessing ground water potentials as part of a totally integrated system that would incorporate (1) existing water resources-related information, (2) remote imagery analysis and interpretation capabilities, and (3) geophysical expertise.

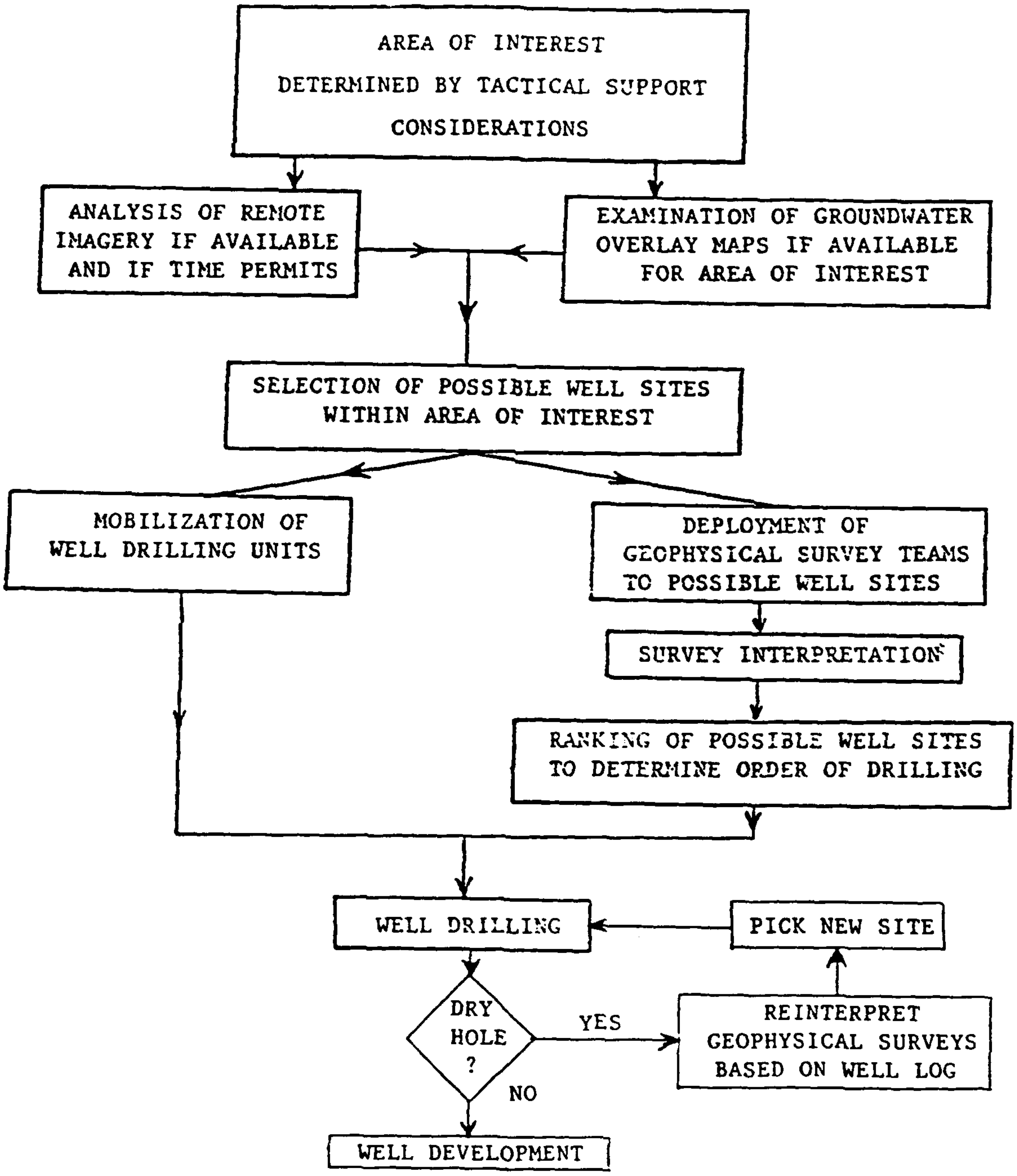


Figure 13. Flow diagram illustrating utilization of geophysical survey team for selection of well sites--resulting in reduced risk of dry holes

References

Butler, Dwain K. and Llopis, Jose' L. 1984. "Assessment of Two Currently Fieldable Geophysical Methods for Military Ground Water Detection," Military Hydrology, Report 6. Miscellaneous Paper EL-79-6, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Butler, Dwain K. 1984. "Assessment and Field Examples of Continuous Wave Electromagnetic Surveying for Ground Water, Military Hydrology, Report 8. Miscellaneous Paper EL-79-6, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi (In Preparation).

Fitterman, David V. 1984. "Interpretation of Transient Electromagnetic Soundings from White Sands Missile Range, New Mexico." Administrative Report, U. S. Geological Survey, Prepared for U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Kaufman, Alexander, A. and Keller, George V. 1983. "Frequency and Transient Soundings." Elsevier Science Publishing Company, New York.

McNeill, J. D. 1980a. "EM 34-3 Survey Interpretation Techniques." Technical Note TN-8, Geonics Limited, Ontario, Canada.

McNeill, J. D. 1980b. "Electromagnetic Terrain Conductivity Measurements at Low Induction Numbers." Technical Note TN-6, Geonics Limited, Ontario, Canada.

McNeill, J. D. 1980c. "EM 37 Ground Transient Electromagnetic System: Calculated Depth of Exploration." Technical Note TN-10, Geonics Limited, Ontario, Canada.

Zohdy, A. A. R., Jackson, D. B., Mattick, R. E., and Peterson, D. L. 1969. "Geophysical Surveys for Ground Water at White Sands Missile Range, New Mexico," Open File Report 69-326, U. S. Geological Survey, Denver, Colorado.

Zohdy, A. A. R., Eaton, G. P., and Mabey, D. R. 1974. "Application of Surface Geophysics to Ground Water Investigations," Techniques of Water Resources Investigations, Book 2, Chapter D1, U. S. Geological Survey, Denver, Colorado.

Waterways Experiment Station Cataloging-in-Publication Data

Simms, Janet E.
Assessment and selection of an automated electrical resistivity interpretation procedure / by Janet E. Simms, Dwain K. Butler ; prepared for U.S. Army Corps of Engineers.
83 p. : ill. ; 28 cm. — (Technical report ; GL-92-12)
Includes bibliographic references.
1. Water, Underground. 2. Geophysics. 3. Hydrogeology. I. Butler, Dwain K. II. United States. Army. Corps of Engineers. III. U.S. Army Engineer Waterways Experiment Station. IV. Title. V. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; GL-92-12.
TA7 W34 no.GL-92-12